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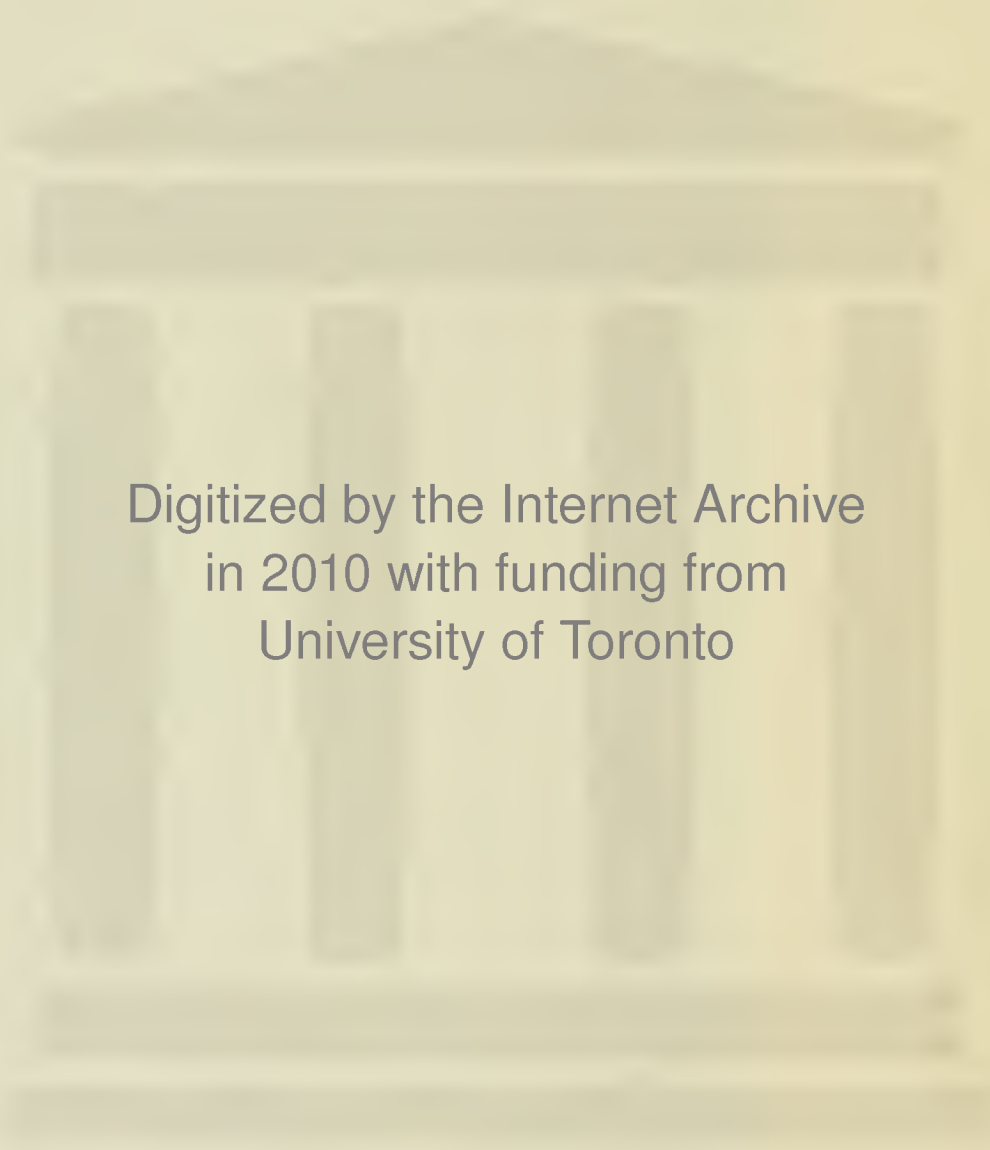

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THE JOURNAL OF

The Institution of Electrical Engineers

ORIGINALLY

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CORRIGENDA.

Page 27, col. 2, line 60, and page 28, col. 2, line 19: *For* "Paton" *read* "Highton."

THE JOURNAL OF
The Institution of Electrical Engineers

Supplement to Vol. 57. [Published, APRIL, 1920.] Part 1.

SOME NOTES ON ELECTRICAL METHODS OF MEASURING BODY TEMPERATURES.

By Robert S. Whipple, Member.

[*Paper first received* 4 *March, and in final form* 27 *May,* 1919; *read at a Joint Meeting of* The Institution *and the* Royal Society of Medicine (Electro-Therapeutics Section) 21 *March,* 1919.]

The first observers to determine by electrical means the temperature of animal tissues were Becquerel and Breschet * (1835), who made use of a single pair of copper-steel couples. The cold junction was maintained at a constant temperature (to within 0·1 degree C.) by means of a thermostat invented by M. Sorel. The thermo-couple, which was pointed, was thrust into the tissues of the animal the temperature of which was being investigated. Some experiments made by Doctors J. Simon and E. Montgomery (1860) with platinum and iron thermo-couples used differentially with an astatic galvanometer, proved that an inflammatory process involves a local production of heat. Other observers worked intermittently with electrical thermometers from this date up to 1908, when the late Professor A. Gamgee commenced his researches on the subject, with a thoroughness and enthusiasm that broke down the experimental difficulties of the research. In a paper on the subject of Clinical Thermometry † he dealt with the history of the subject and pointed out the importance of the study of body temperatures, especially with a view to the study of the preliminary stage of phthisis. He says "the motive which urged me to make the sacrifices of all kinds which this research has involved, was the intense desire to study for the first time, and in an elaborate manner, the normal curve of the temperature of man, and thereafter, in the first instance, the changes which that curve exhibits during the very earliest stages of pulmonary consumption and of surgical tuberculosis, when the organism is the prey of the tubercle bacillus alone and not yet subject to a 'mixed infection'; for I had, by long-continued observations carried out with the clinical thermometer, ascertained the utter want of precision and insight which at present prevails in reference to the very earliest stages of phthisis, when physical signs are yet almost, or completely, in abeyance, and when the cough, the anæmia, the loss of flesh, and slight temperature abnormalities are the only guides the physician has to rely upon." Only those who knew him well know what very considerable sacrifices they were to which he refers.

After a great deal of consideration Gamgee decided to adopt thermo-electric couples in preference to resistance thermometers, and I think it will be generally agreed that for work of high precision his decision was a correct one. The construction of his apparatus is fully explained in his paper, but it may be of interest to give a short description.

The thermometers used were of two kinds, one for taking the temperature of the surface of the skin and the second for the temperature of the cavities of the body. The materials of which the thermo-electric couples were made were copper-constantan, materials which long experience has shown form one of the most satisfactory thermo-elements.

In a thermo-electric couple temperatures are determined by measuring the electromotive force in the circuit, this bearing a definite relation to the difference in temperature between the two junctions of the circuit. This necessitates the control of the temperature of one of the junctions, generally the colder of the two and hence referred to as the "cold junction," the difference in temperature between it and the hot junction, viz. the thermometer in contact with the human body, being determined by the electromotive force recorded by the galvanometer.

Gamgee placed his cold junction in a water bath

* I am indebted to a paper by Professor G. Sims Woodhead and Dr. P. C. Varrier-Jones for this reference. Their paper, which is entitled "Investigations on Clinical Thermometry," is an exhaustive summary of the subject. It fully explains the apparatus used and discusses from the medical point of view the results obtained with the recording thermometers. It also contains a full bibliography. (See the *Lancet* for 22 January, 5, 12, and 26 February, and 4 March, 1916, and also a reprint of the articles published as a bulletin from the Pathological Department, University of Cambridge.)

† A. Gamgee: "On Methods for the Continuous (Photographic) and Quasi-Continuous Registration of the Diurnal Curve of the Temperature of the Animal Body," *Philosophical Transactions of the Royal Society,* Series B, vol. 200, p. 219.

heated by a gas burner, the height of the flame being controlled by a sensitive toluol regulator, the temperature of the bath remaining constant to within 0·01 degree C. during periods of 10 to 15 days. The construction of this water bath is simple. It consists of a double-walled copper vessel (Fig. 1), the space between the walls being filled with a heat-insulating material such as kieselguhr, the inner vessel containing about 50 litres of water. The bath is heated by six small luminous gas flames. When the constant temperature at which the bath is to be maintained, viz. 36·5° C. (98·4° F.), has been reached, five of the burners are extinguished and one is left alight, the gas supply to it being controlled by the regulator. This regulator is the well-known type designed by Lowry and consists of a glass tube bent in the form of a helix containing toluol. The chamber or tube containing the toluol is closed by a small mercury column. Any change in the temperature of the toluol causes a variation in its volume, and hence a movement of the mercury meniscus. This meniscus opens or closes a small aperture admitting gas to the burner under control. The temperature at which the regulator controls is adjusted by means of a screw which raises or lowers the mercury meniscus, thus altering the temperature at which the aperture is closed or opened. The cold junction of the couple is placed in a glass tube containing oil, the standard mercury-in-glass thermometer being either placed in the same tube or in the water bath outside it.

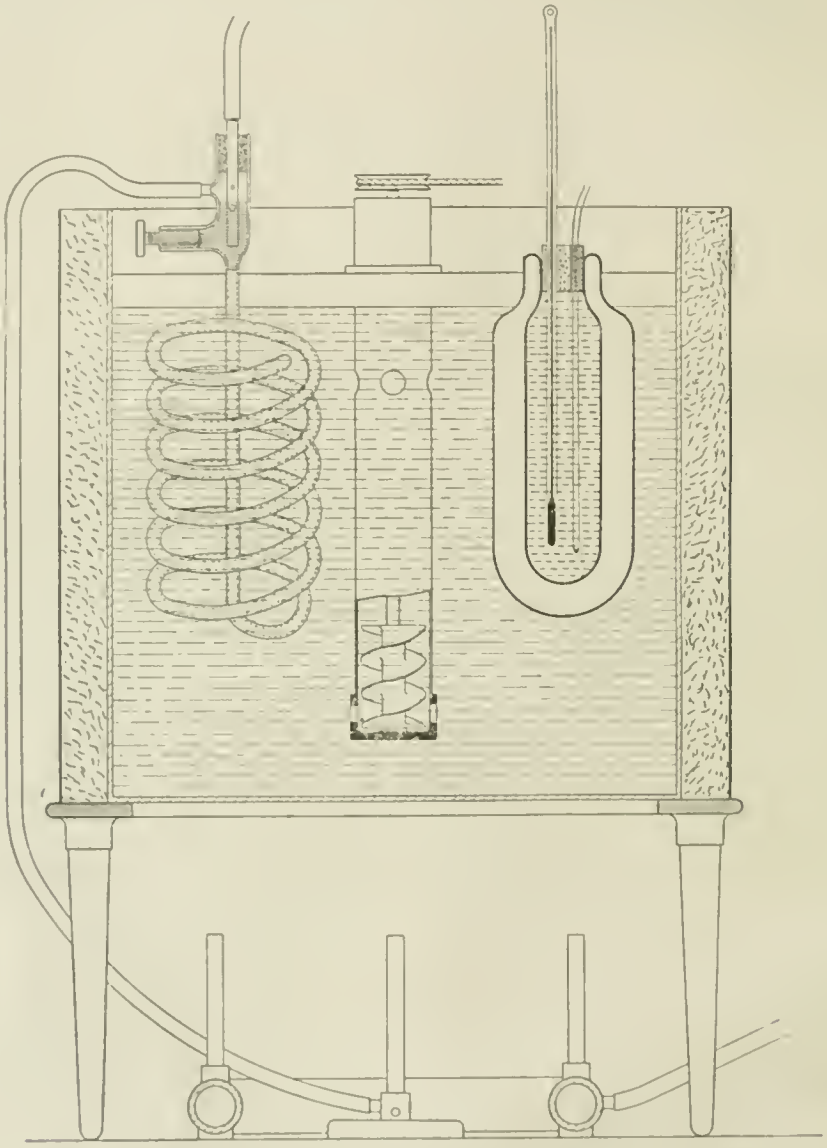

Fig. 1.—Thermostat for controlling the temperature of the cold junctions.

Woodhead and Varrier-Jones, who later on continued Gamgee's work, showed that the regulator was exceed-

ingly sensitive to variations in gas pressure, but by placing the cold junction in a vacuum flask immersed in the water bath they introduced so much lag between it and the water that the temperature remained constant over long periods of time to within 0·01 degree C.*

There is no doubt it would be a considerable help towards maintaining a constant temperature if the gas supplying the controlled burners could be taken from a small gasometer which is independent of the variations in pressure of the town gas-supply.

If it is more convenient to heat the water bath electrically, a modified form of toluol regulator fitted with platinum contacts so that the mercury opens or closes an electric circuit may be employed. This circuit brings into operation a sensitive relay, which in turn makes or breaks the current in the heating circuit. Mechanical stirring can be avoided by the use of slightly compressed air allowed to bubble through the water. A simple water-pump actuated by the town water-supply will give sufficient air pressure.

The Thermo-couples.

A great many types of thermo-couples for determining the skin temperatures were devised by Gamgee, Woodhead, and Varrier-Jones, but the simplest model of all devised by the latter and shown in Fig. 2, has proved to be the most satisfactory. It consists of a copper-constantan couple, the wires of which are

Fig. 2.—Surface thermo-couple.

0·1 mm. (0·004 in.) in diameter mounted between two pieces of canvas embedded in rubber and vulcanized. The approximate dimensions of the couple are 50 mm. × 5 mm. × 2·5 mm., the couple or junction of the two wires being exposed on the surface of the rubber. Stouter wires are soldered to the fine couple wires, and these in turn are attached to the leads connected to the recording galvanometer.

When referring to this thermometer Woodhead and Varrier-Jones state :—" In a thermometer of this type the lag is less than a couple of minutes, the instrument is flat, not too large, easily fixed to the skin in the axilla or groin or, indeed, any part of the body by means of a little strip of plaster ; and causing no inconvenience to the patient, is admirably adapted for taking surface temperatures." In a later part of the paper the authors state that they discontinued the axillary record as they " found it impossible to keep the thermometer in proper contact with the skin for any prolonged period. For short periods admirable records could be obtained, but the patient soon tires of keeping his arm fixed. The difficulty in the lower limb is not so great, as even with considerable movement of the leg or thigh little displacement of the thermometer occurs and there is no inrush of cold air." The author's own experiments confirm this statement. The difficulty in obtaining satisfactory records of the axilla temperatures is largely on account of the anatomy of that part of the body. In the axilla the folds of skin are more or less tightly drawn over that part, thus forming a smooth-walled cavity, whereas in the groin there are scrotal folds which impinge upon the inner side of the thigh, thus affording adequate protection against the inrush of air. The folds of skin in this part thus form a natural covering for the thermometers, and it is when this covering is obtained that the results are so satisfactory. The rectal thermometer as used by Woodhead and Varrier-Jones is very similar to that designed by Gamgee. It consists of a No. 6 rubber catheter (Fig. 3), the couple or junction being embedded in the eye of the catheter and the surrounding space filled with rubber solution which has been allowed to dry. The junction is brought flush with the surface of the rubber tube, where, although fully exposed, it can do no damage to the wall of the rectum. Experience has shown that the thermometer may be left in the rectum without causing inconvenience to the patient for 24 hours or more.

The wires leading from the thermometer are attached to the thigh of the patient by strapping, and are led in spirals from the bed to the recording apparatus. This thermometer also has a lag of about two minutes.

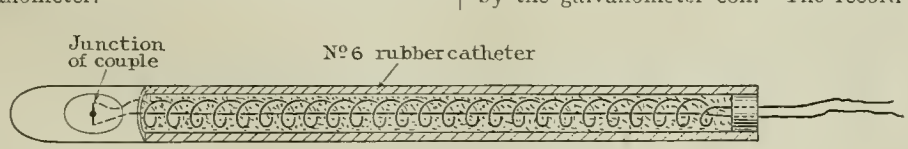

Fig. 3.—Rectum thermo-couple.

The Recording Apparatus.

This consists of a moving-coil galvanometer of the D'Arsonval type, the movements of which are recorded either photographically or autographically by an inking device. In the former method the movements of the coil are indicated by the action on photographic paper of a beam of light reflected from a mirror carried by the galvanometer coil. The record is a continuous one, as the coil is free to move and the beam of light is thrown continuously on the photographic paper.

In the autographic method the galvanometer coil carries a pointer about 150 mm. long, the extremity of which is depressed at intervals (generally every minute) by a clockwork or an electrical mechanism on to either an inked thread or typewriter ribbon, which in turn makes an inked mark on the paper wrapped round the rotating drum. As this method of recording is an intermittent one it was referred to by Gamgee —and the expression has been repeated by subsequent authors—as " quasi-continuous."

The photographic recorder as developed by Gamgee

* " Investigations on Clinical Thermometry," p. 38.

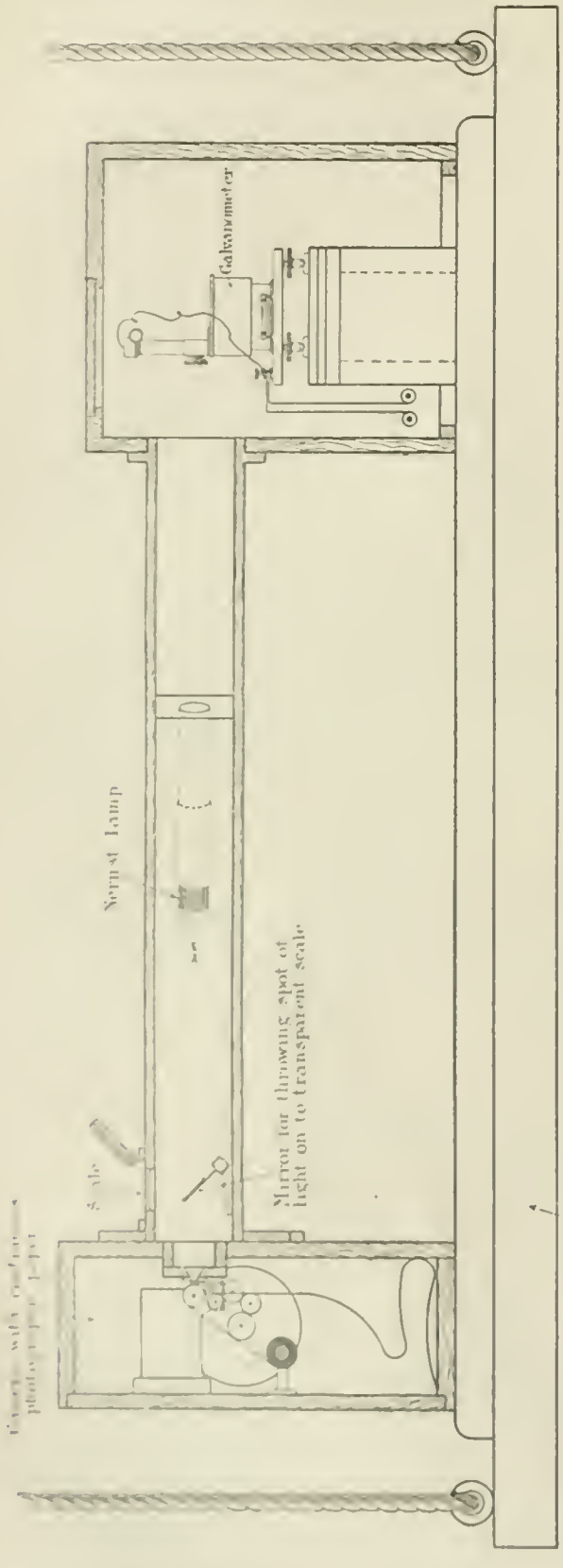
Galvanometer
Nernst Lamp
Mirror for throwing spot of light on to transparent scale
Stone slab suspended by ropes as an anti-vibration table

FIG. 4.—Gamgee photographic recorder.

was a very efficient instrument. It is explained in detail in his paper * and is diagrammatically illustrated in Fig. 4. The galvanometer was of the sensitive moving-coil type, 10·5 ohms in resistance, and gave a deflection of 12 mm. per micro-volt on the photographic paper, which was 116 cm. from the galvanometer. The electromotive force given for a copper-constantan couple is about 40 micro-volts for a temperature difference of 1 degree C. It was necessary therefore to place manganin resistances in series with the galvanometer coil to reduce the sensitivity of the galvanometer and also to reduce the temperature coefficient of the circuit.

The manganin resistance was made adjustable so that varying degrees of sensitivity could be obtained. A sensitivity of about 40 mm. per degree C. was frequently employed, although for special cases 120 mm. per degree C. could be used. The bromide photographic paper (200 mm. wide) was moved by clockwork at a rate of 1 mm. per minute. By means of a shutter a beam of light from a fixed mirror was occulted every half-hour so that a time scale was marked on every record sheet. This record also formed the zero reference line, the distance of any point on the temperature curve from it being a measure of the temperature at that point. The optical arrangements of this instrument were particularly simple and efficient. The source of illumination was a Nernst lamp, and the image of a slit in front of the lamp fell on a very narrow horizontal slit placed close to, and in front of, the photographic paper. Owing to the fact that quartz mirrors platinized on the front surface were employed, and that no light was lost by absorption in intermediate lenses, the definition of the records was exceptionally good. A reproduction on a reduced scale (half full size) of a small piece of a record is given in Fig. 5.† This shows well the sensitivity of the apparatus.

In accurate research work no autographic recorder can compare with a photographic one, but it is cumbersome and the cost of running it is too great for ordinary clinical work. Gamgee himself felt this, and in his paper referring to one of the autographic recorders he states that "it is my opinion that . . . the thread recorder of Mr. Horace Darwin will be the practical instrument of clinical investigation." ‡

The thread recorder to which Gamgee refers is one variety of a number of quasi-continuous recording moving-coil galvanometers. As a large number of these instruments are in use for recording temperatures, and several for the recording of body temperatures, it may be of interest to describe the instrument in some little detail, more particularly as the instrument is also used with resistance thermometers for recording body temperatures. The essential parts of the instrument are shown in Fig. 6. It consists of a moving coil T suspended between the poles of a permanent magnet N S. A pointer E is attached to the coil and overhangs the paper on which the record is to be made. This paper is wrapped round a drum which rotates by clockwork

* *Philosophical Transactions*, Series B, vol. 200, p. 232.

† This figure, as well as Fig. 7, is reproduced by the courtesy of the Royal Society.

‡ *Philosophical Transactions*, Series B, vol. 200 p. 239.

once in 25 hours. Immediately over the paper an inked thread B is stretched parallel to the axis of the drum. A presser bar C is placed above the galvanometer pointer and this bar is normally held free of the pointer by means of the cam mounted on the shaft D. Every 60 seconds the cam makes half a revolution,

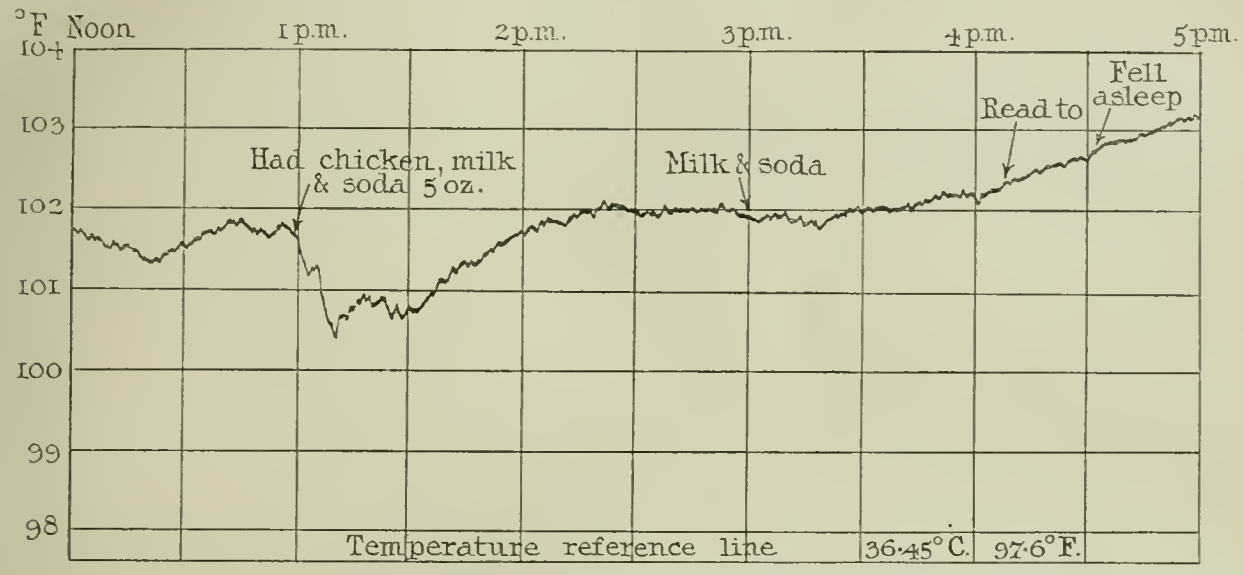

Fig. 5.—Temperature record obtained with the photographic recorder (half full-size).

allowing the presser bar to fall upon the pointer E and then raising it again to its normal height. As the presser bar falls it depresses the pointer on to the drum, nipping the inked thread between the pointer and the paper. This produces a dot upon the paper at the point of the intersection of the pointer and the thread, thus making a visible record of the instantaneous deflection of the galvanometer. In the intervals between the production of the dots the galvanometer is, of course, free to take up its true deflection without frictional errors. Owing to the slow rate at which the drum rotates, 12·5 mm. per hour, the dots made by the galvanometer boom pressing upon the inked thread once a minute coalesce into an almost continuous curve (see Fig. 7). In the other type of quasi-continuous recorders a typewriter ribbon is used instead of the inked thread. This has the drawback that the ordinates of the curve obtained are circular and not rectangular. The sensibility obtained on one of these recorders when used with a copper-constantan couple is more than sufficient for clinical work, viz. 12 mm. deflection on the record sheet for a change in temperature of 1 degree C.

Fig. 7 is a reproduction of a record obtained by Gamgee, and the following note with regard to this record appears in his paper * :—

" The curve in a case of pneumonia, almost certainly of tubercular origin, taken with the thread recorder. At 10 p.m., paracentesis of the left pleural cavity was performed to withdraw the greater part of a large effusion which had formed. The operation was followed by a rise in temperature from 104·2° F. to about 105·3° F., probably in great measure accounted for by the incessant coughing of the patient. At 1.25 a.m. a dose of the hospital ' linctus,' containing 12 drops of liq. morph. hydroch., was administered. The cough was almost at once relieved, and at 3.25 a.m. the patient fell asleep, when the temperature sank almost suddenly, as shown by the curve, to 100·5° F. This curve, which represents all the temperature changes during 38 hours 30 minutes, illustrates admirably the value of the method of registration under discussion." Unfortunately it has only been possible to reproduce the first few hours of this record. The full record is given in the paper mentioned.

As previously stated Gamgee, after a great deal of thought, decided to adopt the thermo-electric couple in preference to the resistance thermometer, believing that the small mass of the couple would enable him to measure temperature changes more rapidly than the resistance thermometer which, of necessity, must be larger than the couple. At the time he knew the work carried out by Professors Attwater and Benedict,* and he also knew that Sir Ronald Ross had used a resistance thermometer † and Callendar recorder to obtain continuous temperature curves. Callendar—who has carried resistance thermometry to its present high state of perfection—also devoted a great deal of time to the designing of resistance thermometers for clinical work. In his Presidential Address to the Physical Society in 1910,‡ which was also a memorial lecture to Professor Gamgee, he described the various thermometers he had made, and discussed their relative advantages. He mentions that Gamgee " had become

* *Philosophical Transactions*, Series B, vol. 200, p. 240.

* For a summary of their work see " A Respiration Calorimeter with Appliances for the Direct Determination of Oxygen," by W. O. Attwater and F. G. Benedict. Published by the Carnegie Institution of Washiogtoo, 1905.

† The Platinum Thermometer and Callendar's Electric Recorder for obtaining continuous clinical temperature charts, *Lancet*, i. 585.

‡ H. L. Callendar: *Proceedings of the Physical Society of London*, 1910, vol. 22, p. 220.

convinced that the thermo-electric method was unsuitable for general use, on account of the delicacy of the apparatus, and the necessity of employing an elaborate thermostat. . . . In the application of the resistance method no thermostat was required, and it was easy to obtain a tenfold larger deflexion with the same galvanometer." Woodhead and Varrier-Jones also of the quasi-continuous type and not very dissimilar to the thread recorder, with the exception that the ordinates were circular and not rectangular.*

Experience has shown that if a rectal thermometer is used, the resistance coil—assuming it is correctly designed and made—follows the temperature changes in the body without appreciable lag. The mass of the

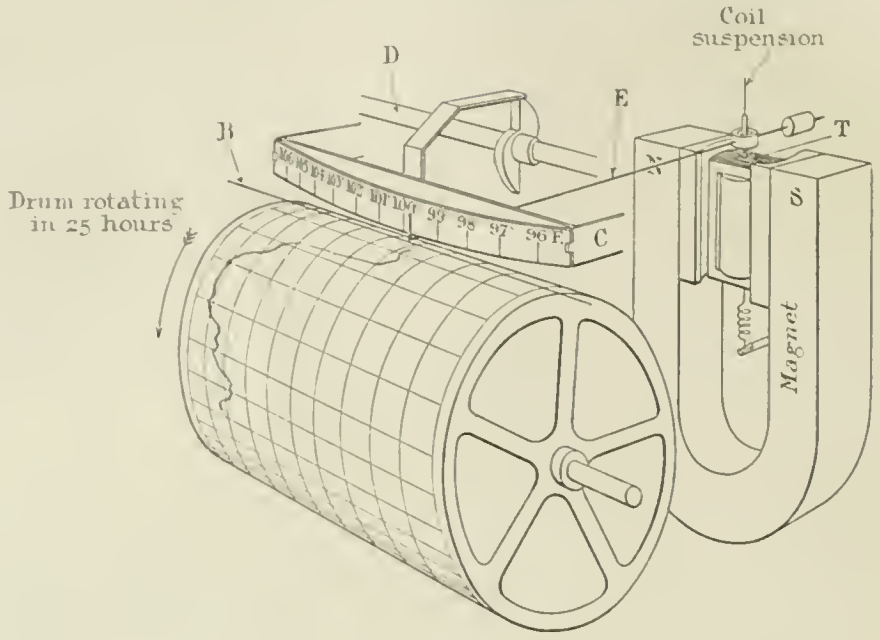

FIG. 6.—Essential parts of thread recorder.

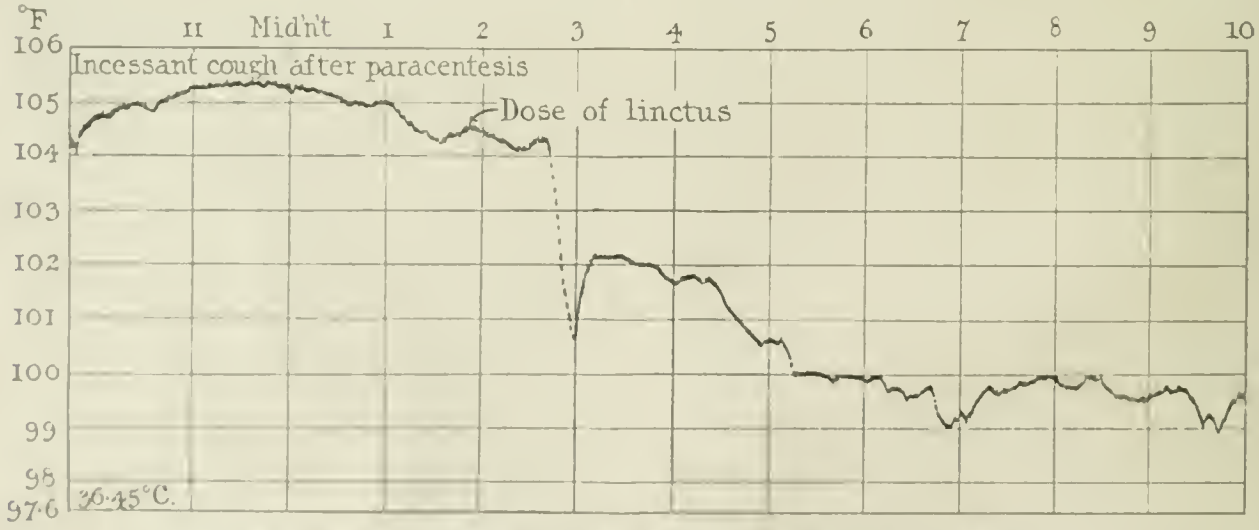

FIG. 7.—Record obtained with a thermo-couple and thread recorder (full size).

came to the same conclusion and decided to use resistance thermometers.

In the interval between these workers Eichler and Schemel working with resistance thermometers and a Siemens and Halske recorder had obtained some excellent records of body temperatures. The recorder was

thermometer is small compared with the mass of the human body. If the protecting tube of the ther-

* Über die Beeinflussung der Magentemperatur durch verschiedene hydrotherapeutische Applicationen und ihre Messung mit dem "Ebner-registrierapparat" (nach Siemens und Halske), *Deutsch. med. Wochenschr.*, 1911, Leipzig, vol. 48, p. 2171, and Über Temperaturmessungen im Darm mit dem Ebner registrierapparat von Siemens und Halske bei verschiedenen hydrotherapeutischen Massnahmen. *Berlin. klin. Wchnschr.*, 1912, vol. 49, p. 60.

mometer is made of a good heat conductor, such as silver, the thermometer attains the body temperature rapidly, especially as it is moistened with the mucus of the rectal passage.

For clinical work the resistance thermometer offers the great advantage that the apparatus is robust and simple.

The thermometer, the particular design of which is

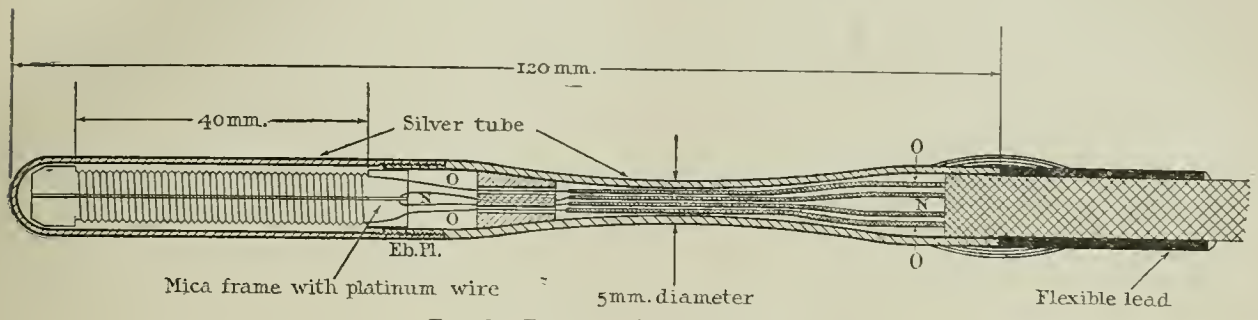

FIG. 8.—Rectum resistance thermometer.

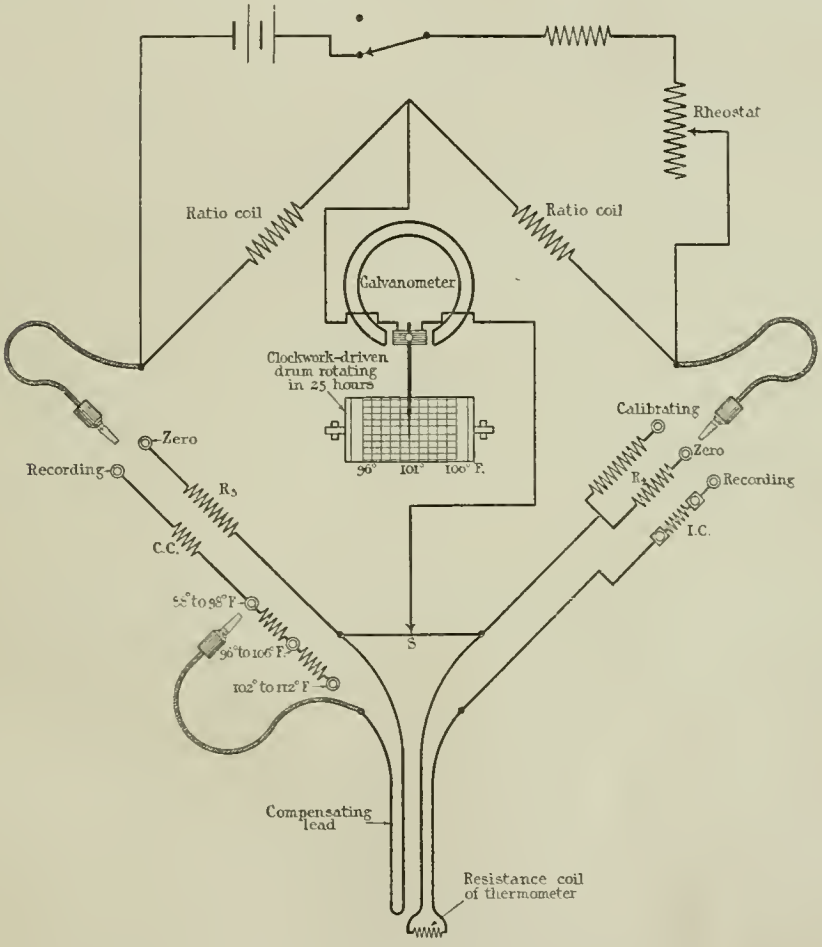

FIG. 9.—Diagram of resistance thermometer circuit.

As has been previously explained, the difficulties of making satisfactory surface thermometers and of attaching them to the patient are considerable, and need therefore not be discussed in connection with resistance thermometers, where the difficulties are even greater than with thermo-couples.

due to Dr. Varrier-Jones, is shown in section in Fig. 8. The essential part of the thermometer is a fine platinum wire wound round a mica frame in the form of a cross, the coil on its frame being enclosed in a silver tube. This tube is constricted so that it may not irritate and thus stimulate the contraction of the sphincter

muscle. The thermometer coil is connected by comparatively heavy copper leads to the instrument on which the temperature is to be recorded. The electrical details of the arrangement are shown diagrammatically in Fig. 9. The arrangement consists of a Wheatstone bridge in which the thermometer forms one arm, balancing coils being arranged in the opposite arm to balance the resistance of the thermometer at any predetermined temperature. Ratio coils of equal resistance and of approximately the same resistance as the thermometer are inserted in the other arms of the bridge. It will be observed that in addition to the leads attached to the thermometer coil two other leads, or compensating leads, are carried from the thermometer to the recorder. These leads are short-circuited near the bulb of the thermometer, and are introduced into the opposite arm of the bridge to compensate for the effect of changes in temperature on the leads.

The galvanometer, which is of the moving-coil type, is connected across the arms of the bridge and it is the deflections of the coil that are recorded. For the small angle through which the coil is deflected (maximum about 25°) the deflections are proportional to the amount the bridge is out of balance, viz. to the change in resistance of the thermometer coil with a given change in temperature. In a direct deflection method such as this, it is obvious that the galvanometer deflection must depend on the electromotive force of the battery, and what few complications there are in the apparatus have had to be introduced to control this. The method of adjusting the apparatus is simple.

Before the battery circuit is closed, viz. with the switch in the "off" position, the zero of the galvanometer is determined. This should be on the line corresponding to the lowest temperature (say 96° F.) recorded by the thermometer. If it is not, the pointer is readily brought into the desired position by rotating the torsion head from which the galvanometer coil is suspended.

The electrical zero of the bridge—the one in which no current is passing through the galvanometer coil when the battery switch is closed—is then determined. The plugs attached to the heavy flexible leads, and shown symmetrically on both sides of the diagram, are placed in the zero positions. It will be observed that the thermometer coil and its leads, and the corresponding balancing coils and compensating leads, are then cut out, the ratio coils being balanced against the coils R_3 and R_4. If when the switch is closed the galvanometer is not deflected, the electrical zero is correctly adjusted. If it is deflected, the slider s is moved on the slide wire until balance is restored. The instrument must then be adjusted so that the galvanometer coil is deflected through a definite angle for a given change in the resistance of the thermometer. Experience showed that the making of the test by heating or cooling the thermometer was tedious, and as the test should be made every 24 hours it was advisable to introduce a test resistance which would be equivalent to an increase in the resistance of the thermometer for a given change in temperature. In practice a manganin coil having a resistance equal to the increase in resistance of the thermometer coil for a rise in temperature of 10 degrees F. is used. This is marked "calibrating" and is shown in the right of the diagram. When this is introduced the galvanometer should be deflected and the pointer should read 106° F. If it reads low then the electromotive force on the bridge is not sufficiently high and should be raised by cutting out some of the battery resistance by means of the rheostat. In the same way if the galvanometer reading is too high the electromotive force should be reduced. In the later form of the instrument the sensibility is altered by an adjustable magnetic shunt, thus avoiding the use of a rheostat.

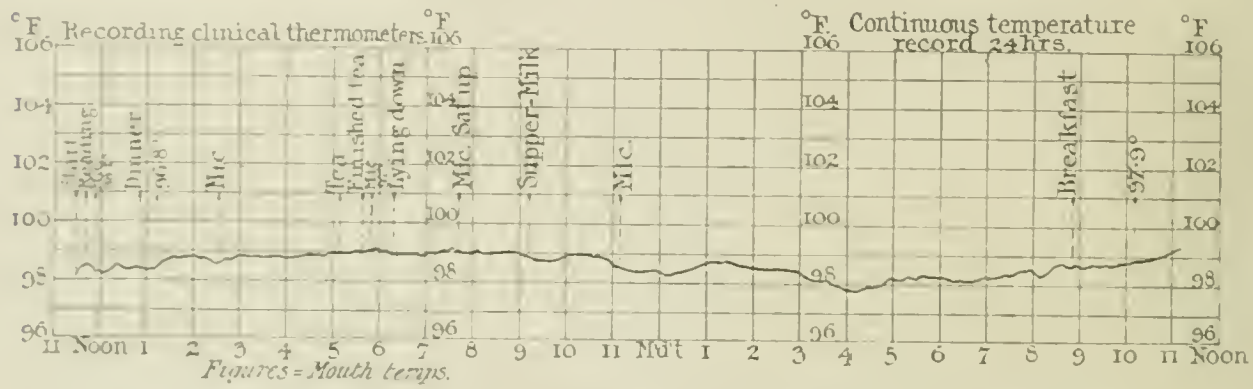

FIG. 10.—Record obtained with a resistance thermometer and thread recorder (about half full-size).

These various adjustments having been made, the two plugs are placed in the "recording" position and the apparatus is ready for use. The travelling plug (Trav.) is placed in the hole corresponding to the temperature range desired, the usual one being 96° F. to 106° F. By introducing or cutting out the coils shown in the arm of the bridge opposite to the thermometer, the range over which records can be obtained may be varied. The ranges generally used are 88° F. to 98° F., 96° F. to 106° F., and 102° F. to 112° F.

The thermometer should be slightly warmed and

covered with a thin film of vaseline before being introduced into the rectum. It will record the temperature of the body in about 5 minutes after insertion. A record obtained with a thread recorder and resistance thermometer is reproduced half size in Fig. 10. This record was obtained by Dr. Varrier-Jones and is reproduced by his courtesy.

In practice the outfit is simple to operate, an observer learning in an hour how to make the adjustments and to manipulate the instrument. As in the case of all scientific instruments, the best work will be obtained by the manipulator who has an affection for instruments and patience in handling them. Nevertheless, the recorder and its accessories are so simple that to the medical man accustomed to using some of the modern medical-electrical apparatus the instrument can be regarded as another tool added to clinical medicine.

Summarizing the experiments of the chief workers in the subject from the instrumental point of view, it may be said that:—

(1) A continuous record of the temperature of the human body can be best obtained by an electrical thermometer placed in the rectum.
(2) For accurate research work when it is desired to record variations in temperature to an accuracy of 0·02 degree C., a thermo-electric couple must be used in conjunction with a photographic recorder.
(3) If rapid or very small variations in temperature are being recorded a photographic recorder must be used.
(4) For ordinary clinical work a resistance thermometer with an autographic recorder is the most practical instrument. It can be relied upon to record body temperatures to an accuracy of at least 0·1 degree C.

In conclusion, it is only right to state that if it had not been for the help and instigation of Professor G. Sims Woodhead and Dr. P. C. Varrier-Jones the apparatus would not have reached its present practical stage. I have warmly to thank Dr. Varrier-Jones for reading through the manuscript of these notes, and for many suggestions.

Technical Data.

Recording thermo-electric couple.

(1) Photographic recorder (Gamgee model).
D'Arsonval galvanometer coil resistance (copper)=about 10·5 ohms.
Balancing resistance in circuit to give a scale deflection of 35 mm. per degree C. (about 21 mm. per degree F.)=about 400 ohms.
Scale distance, 116 cm.
Diameter of galvanometer mirror, 10 mm.
Width of photographic paper, 200 mm.
Speed of paper, 60 mm. per hour.

(2) Quasi-continuous recorder (thread recorder model).
D'Arsonval galvanometer coil resistance (copper)=about 6 ohms.
Balancing resistance in circuit (manganin), 4 ohms, to give a scale deflection of 12 mm. per degree C. (about 7 mm. per degree F.).
Width of record sheet, 80 mm. (96° F. to 160° F.).
Speed of paper, 12·5 mm. per hour; or on fast speed 300 mm. per hour.

Thermo-electric couple.

Copper constantan (60 per cent copper, 40 per cent nickel).
E.M.F. = approximately 40 micro-volts per degree C. (22·2 microvolts per degree F.).

Recording resistance thermometer.

Quasi-continuous recorder (thread recorder model).
D'Arsonval galvanometer coil resistance about 70 ohms.
Balancing resistance (manganin) in series with galvanometer coil about 70 ohms.
Equal ratio arms of bridge, about 200 ohms.
Scale deflection, 17 mm. per degree C. (9·5 mm. per degree F.).
Width of record sheet, 95 mm. (96° F. to 106° F.).

Resistance thermometer.

Platinum coil made of 0·05 mm. (0·002 in.) platinum wire, resistance at 60° F. about 140 ohms.
Change in resistance per degree C.=0·54 ohm (per degree F.=0·3 ohm).

Discussion.

Professor Sims Woodhead, M.D.: It will be realized from what has been said what a tremendous advantage it is for us to have the Cambridge Scientific Instrument Company interested, first in Professor Gamgee's work, and then in the continuation of that work. With Professor Gamgee's apparatus it was possible to obtain records of temperature with little lag and accurate to about 1/200th of a degree. By the other resistance-thermometer method such delicate accuracy cannot be obtained, but the results are of equal practical value. In order to show what can be done with these instruments, I will exhibit a number of lantern slides and make a few remarks upon them as they appear, drawing attention to one or two very marked features in the temperature variations, first of the normal individual, and secondly of the tuberculous patient. My interest in this work was aroused in about 1879. I then learned, curiously enough, that Professor Gamgee had already, about a year or two years before, been occupied in the same kind of work. I went to my old teacher, Professor Tait, who informed me that it was practically impossible to obtain the results I aimed at, as he and Arthur Gamgee had been able to find no galvanometer that would give them satisfactory results. When Professor Gamgee came to Cambridge and re-engaged on this work we naturally were all very much interested in it, and I think those who saw his work realized at once how important this or some similar

method of recording temperatures was likely to become. Those who have had experience of the recording of temperatures of tuberculous patients, and especially of patients tested with tuberculin—and this is well known in the veterinary profession—will realize that a number of factors or points very difficult of explanation are met with in connection with these tuberculin tests. The difficulty, for example, of determining the highest and lowest temperatures attained during the pre-tuberculin and tuberculin period is very great. But if a continuous or semi-continuous record can be obtained, the lowest and highest temperatures at any part of the day—in fact the temperatures attained at any part of the 24 hours—can be observed and recorded both before and after tuberculin is injected, and if necessary so long as the tuberculin continues to have any effect. In many cases the tuberculin test has been said to fail: in 5 or 10 per cent of the cases it has no doubt failed to give the results expected, or the results that were hoped for. These records show, I think, how easy it is to determine the difference in temperature between the pre-tuberculin and the tuberculin stage in a tuberculin test. It will be seen how even the normal temperature varies from hour to hour, also the nature of the temperature curve, i.e. the period over which there is the greatest difference between the pre-tuberculin and the tuberculin curves, the points at which the temperature begins to rise and at which there is a gradual fall, and how variations occur under different conditions. If the temperature varies considerably during the normal or pre-tuberculin period, it is found that the variation is even greater when tuberculin has been given. Similar variations will be found characteristic of the temperatures of tuberculous patients; these also are increased by the exhibition of tuberculin in very minute quantities. One finds, too, that the temperature of tuberculous patients is often extremely unstable. Rapid variations occur and, instead of having a comparatively straight line with slight curves, the record, especially when compressed laterally, appears as a dentate line, the teeth apparently being the result of causes which in the normal patient or animal have little effect. The same holds good in the case of the tuberculinized animal. (Professor Woolhead then showed a number of slides.) I wish to draw attention to the fact that we can gain from this form of record an amount of information which up to the present we have not been able to obtain. I believe that in many fields of medical and surgical research this will be a factor of great value. In the case of "trench fever," for example, we could probably obtain a considerable amount of information by this method if applied over a considerable period. I am sometimes spoken of as a "faddist" on the question of alcohol. It was in connection with the action of alcohol on the human body that I first undertook this work. The results obtained appeared to me to be so important that I asked and received the co-operation of Dr. Varrier Jones and Mr. Whipple. The results obtained are already of considerable value, but by this method we shall, I believe, obtain results of still greater importance. One great feature of the apparatus, not yet mentioned, is that it covers great range of temperature, something like 18 degrees, may be recorded with extreme accuracy over long periods. By its use the tuberculin reaction may be studied in great detail, and is found to be very different from what it has hitherto been regarded. I can only say, in conclusion, that I hope the temperature changes in many diseases will be investigated by means of this apparatus. This can be done very easily and without alarming the patient, as the recording apparatus may be erected and read off in the laboratory whilst the patient remains in bed in the hospital.

Dr. P. C. Varrier-Jones: When we turned our attention to taking the temperatures of cattle in connection with the tuberculin test we found that the thermo-couple was rather too delicate for the work we had in hand. The resistance thermometer was found to be more suitable for taking the temperatures of cows, whether they were suffering from tuberculosis or not, the apparatus being more strongly constructed and not so liable to snap or break. We were able in the case of cattle to take very long records. It was quite simple to take records of patients over half an hour or an hour, but the difficulty was to retain the thermometer in situ for a longer time, especially in cattle. However, we were fortunate in so arranging the apparatus that we could take records for three or four days one after the other, so that we could see accurately how long a dose of tuberculin acted on the animal. With regard to tuberculous patients, we find that the apparatus as now designed is perfectly simple to use. The patient does not object to it in the slightest degree, and we are now working at the question of devising a method for the early diagnosis of phthisis. With regard to the temperature of persons suffering from phthisis, we find we can reproduce in the patient the exact conditions that we have in calves which are experimentally tuberculized. The records are practically identical, so that we can get—from the very small rise in an early case of phthisis after giving small doses of tuberculin—the "plateau," and we can, by means of exercise, produce in a person with well-advanced disease the upside-down curve which is characteristic of an animal having a tremendous amount of tuberculous disease. The patients do not object to this record being taken for considerable periods of time. The little skin thermometer can be used for 20, 24, or 26 hours. After that the surface thermometer is not yet reliable, but the resistance thermometer can be used with absolute certainty.

Professor A. W. Porter: I should like to emphasize the extraordinary difficulty there is in the determination of surface temperatures such as that of the skin. The actual determination of the temperature of the external point of the surface is, as every physicist knows, a matter of great difficulty, and I am not quite sure to what extent that difficulty has been overcome in the case of the simple thermo-couple arrangement which has been described, although perhaps there is no serious defect in it so far as the determination of the *variations* of temperature are concerned. That variation is what, I suppose, especially concerns medical men. The actual temperature is probably quite uncertain. The difficulty is that no matter in what way the thermo-

couple is applied, one must modify the conditions of radiation in the neighbourhood of that point, and especially when the thermo-couple itself is surrounded by an indiarubber container, as I understand it is. This container, when placed upon the surface of the skin, must of course tend to prevent not only radiation but also evaporation from the surface, upon which largely the temperature of the surface depends, and I should like to know to what extent experiments have been made towards determining the magnitude of that effect. It would seem to me that it might be better if the actual extent of the surface pad were reduced. I observed that in the first diagram the thermo-couple itself is entirely placed at one end. Why should the pad be any more extensive than that represented by a square of which the thermo-couple is the centre? The rest, if it is intended as a support to the leading-in wires, could be placed at right angles to the surface. I believe there would be in that case less tendency to disturb the surface conditions than in the actual arrangement.

Dr. A. O. Rankine: There is much to be said in favour of the thermo-couple as a means of determining quickly-changing temperatures. It will have very little thermal capacity and should record the temperature very soon after being placed in position. I was very interested to see the diagrams which the author showed in connection with the thermostat used, but it is difficult to see why it was necessary to have such an elaborate arrangement. The obvious procedure would seem to be to put the second couple, not into a thermostat, but into a suitable mixture of ice and water, the temperature of which would be quite constant without any elaborate precaution for keeping it so. It is true that in that case we should be measuring a larger difference of temperature, but it ought to be possible to control by external means the galvanometer movements, so as to keep the indicator on the scale. I suppose it is admitted that from the medical point of view it is the difference between the temperature of the patient and the normal which is most important. It is clear from the diagrams that there are ordinarily, quite apart from illness, variations to be expected from time to time in the temperature of the normal person, and I wonder whether it would be impossible to employ a sort of standard man who would be kept in good health and to whom the second thermo-couple could be permanently fitted.

Mr. E. H. Rayner: Reference has been made to the fact that something of the order of 1/200th of a degree Centigrade can be measured in practical hospital working on an apparatus of this nature, both by the resistance method and by the thermo-couple method. To show what this means, one may take it that all ordinary pure metals change something like 3 or 4 parts in 1,000 per degree Centigrade, so that when we read to 1/100th of a degree Centigrade we are measuring with reasonable accuracy changes of 3 parts in 100,000. In an electrical laboratory with elaborate apparatus this is fairly easy; but to be able to do it by intelligent but not highly skilled people in a hospital by the bedside is a very great compliment to the ingenuity of the Cambridge Scientific Instrument Company. Again, when dealing with thermo-couples one naturally chooses the most convenient metals or alloys which will give the largest thermo-electric voltage per unit difference of temperature. For many purposes one uses constantan and iron, and for each degree difference of temperature in the two junctions we get in practice 1/20,000th of a volt, and 1/100th of a degree represents about one two-millionth of a volt. That again is not a difficult thing to do in a laboratory, but to do it in a portable instrument by the bedside is a very considerable achievement.

Dr. E. P. Cumberbatch: I understand from the author that his apparatus will record such small temperatures as 1/100th of a degree Centigrade. If that is the case, his apparatus ought to be of considerable use in determining the path through the tissues of electrical currents of high-frequency oscillation. During the past few years I have been using these currents for the purpose of raising the temperature of different parts of the body, especially the interior parts. From inquiries which I have made amongst physicists, I have been unable to discover exactly what is the path of these currents through the tissues of the body, but if we have an apparatus which can detect a difference of 1/100th of a degree Centigrade we might be able to determine more exactly what is the path of the current through the body as shown by its power of raising the temperature of the deep and superficial tissues.

Mr. F. C. Raphael: It is very gratifying that these instruments should place at the disposal of medical men another method of getting quantitative measurements. Although the instruments are beautifully worked out, I do not think it is right merely to look at the measurement as a measurement of about 100 degrees Fahrenheit to an accuracy of 1/100th of a degree Fahrenheit. What is really being measured is a difference in temperature, and consequently there is not such a very high degree of accuracy necessary in the measurement itself. It is rather in the method of application and in the small size of apparatus to be dealt with that the value is to be found. Consequently I think Dr. Cumberbatch, for instance, need not despair at all of being able to apply the apparatus or a somewhat similar one to the measurements which he indicates. What I have said answers the question put by another speaker: Why should not the so-called cold junction be put in melting ice? The reason is obvious. The cold junction must be kept at a temperature very near to the temperatures we are measuring, because we are measuring a difference, and we want that difference to be as small as possible, so that the actual inaccuracy of our measurement may be as small a percentage as possible.

Mr. R. S. Whipple (*in reply, communicated*): Professor Porter touched on the difficulties to be overcome when the skin thermometer is used. In conjunction with Professor Gamgee a great many experiments were made to find the best type of mounting for the sensitive element. Gamgee thought that the mounting over the couple tended, by conduction, to lower the temperature of the skin at the point of contact, so that he aimed at reducing heat losses rather than preventing evaporation from the surface of the skin. To do this to the maximum extent, a couple was mounted on the face

of a small, flat, exhausted, and silvered glass vessel. This should have almost entirely prevented radiation losses. It was found to give no more satisfactory results than the cloth pad. The great difficulty is to obtain intimate contact between the thermometer, whether it is of the resistance or thermo-couple type, and the skin. If a thin film of grease is introduced between the thermometer and the skin, the result is better than if only the moisture of the skin is relied upon. A great many forms of mounting were tried with pads of various areas, and yet no absolutely satisfactory method was found for keeping the axilla thermometer in contact with the skin. On the other hand, the rectum thermometer is surrounded by moisture and hence its more satisfactory behaviour

As Mr. Raphael pointed out, it is not possible to use ice and water as a method of keeping the cold junction at a constant temperature as suggested by Dr. Rankine. Temperature differences are being measured and the difference between body temperature and the temperature of molten ice is far too great to be readily covered by the sensitive galvanometer used in these experiments. The "standard man" suggested by Dr. Rankine has already been designed and used in the form of a very small electrically-heated space, the temperature of which is controlled by a bi-metallic thermostat. It works well, but as the water bath is more satisfactory in practice I did not mention it. I agree with the statement that an accuracy of one-tenth of a degree Centigrade is sufficient for nearly all medical work; Professor Gamgee undoubtedly aimed for an accuracy of one-hundredth of a degree Centigrade.

I was much interested in Dr. Cumberbatch's remarks. I think it may be possible to measure the rise in temperature of the surface of the skin when a patient is undergoing high-frequency treatment. There is the risk that eddy currents in the thermometer may vitiate the records, and there will undoubtedly be other difficulties, all of which can only be determined, and perhaps solved, experimentally.

SOME NOTES ON THE ELECTRO-CARDIOGRAPH.

By Robert S. Whipple, Member.

[*Paper first received* 10 *March, and in final form* 27 *May*, 1919; *read at a Joint Meeting of* The Institution *and the* Royal Society of Medicine (Electro-Therapeutics Section) 21 *March*, 1919.]

Professor A. W. Waller was the first physiologist to show * that the electric potentials developed in the heart at each contraction of the organ were sufficiently large to deflect a sensitive galvanometer when the latter is connected to the limbs of the human subject.

Little progress was made from this discovery until the invention of the string galvanometer in 1901 by Professor W. Einthoven, the eminent physiologist, at the University of Leyden.†

As there has been some little controversy as to the priority of the invention of the string galvanometer it may be as well to state briefly the facts of the case. A string galvanometer was invented by Ader and described by Léauté before the French Academy of Sciences in 1897. A detailed description of the instrument by F. Rossel will be found in *L'Eclairage Electrique*, 1897, p. 295. The instrument was developed as a recorder for submarine telegraphy, Rossel pointing out the advantages of the small moment of inertia and short periodic time of the moving system compared with other galvanometers. The magnetic field was given by a large laminated permanent magnet. In the gap of the magnet (about 0·5 mm.) a copper or aluminium wire 75 cm. long and 0·02 mm. in diameter was stretched, the centre of the wire being thickened by means of a feather quill. Although intended for submarine cable work the instrument did not come into general use. Considered as an electrical measuring instrument it is about 100,000 times less sensitive than the modern string galvanometer. The instrument designed by Einthoven was of an entirely different character, having a powerful electromagnet and a comparatively short silvered quartz fibre as the moving system. It was invented by him without any knowledge of Ader's instrument and from theoretical considerations only. When calculating the constants for a sensitive moving-coil instrument he found that the smaller the number of windings on the moving coil the greater the normal sensitivity of the galvanometer. A coil consisting of a single winding of a very fine fibre is the most sensitive. Instead of the single winding he took the stretched fibre.

In its main features the galvanometer is still in the form in which Einthoven made it, although it has been simplified by various workers so as to render it convenient for clinical work. Largely as a result of Einthoven's work* and that of Dr. Thomas Lewis† an important branch of pathology, electro-cardiography, has arisen. As this science is dependent on the interpretation of the records obtained with the string galvanometer it may be of interest to describe the instrument and its accessories in some detail.‡

The problem may be briefly stated. If the extremities of the limbs of a patient, such as the two hands, are placed in non-polarizable electrodes, and electrical

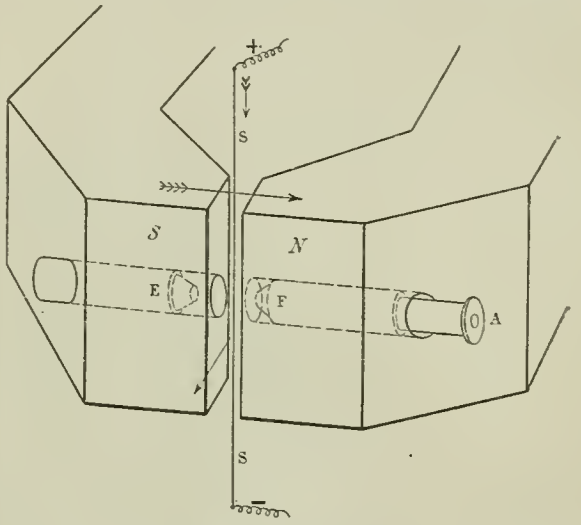

Fig. 1.—Diagram showing the principle of the string galvanometer.

connection is made through the galvanometer, the string is deflected by the current passing through it.

* "A Demonstration on Man of the Electromotive Changes Accompanying the Heart's Beat," *Journal of Physiology*, 1887, vol. 8, p. 229.

|† "Ein neues Galvanometer," *Annalen der Physik*, 1903, vol. 4, p. 1059; also "Die Konstruktion des Saitengalvanometers," *Archiv für die ges. Physiologie*, 1909, vol. 130, p. 287.

* W. Einthoven and K. de Lint: "Über das normale menschliche Elektrokardiogram," *Archiv für die ges. Physiologie*, 1900, vol. 80, p. 139.

W. Einthoven: "Enregistrement Galvanométrique de l'Electrocardiogramme humain, etc.," *Archives Néerlandaises des Sciences Exactes et Naturelles*, Series II, vol. 9, p. 202.

W. Einthoven: "Weiteres über das Elektrokardiogramm," *Archiv für die ges. Physiologie*, 1908, vol. 122, p. 517.

† See "The Mechanism of the Heart Beat," "Clinical Disorders of the Heart Beat," "Clinical Electro-cardiography," etc., by Dr. Thomas Lewis, all published by Messrs. Shaw & Sons, Fetter Lane, London. A full bibliography of papers dealing with electro-cardiography will be found in Dr. Lewis' book, "The Mechanism of the Heart Beat."

‡ This statement is not absolutely correct, as a very sensitive oscillograph has been developed by the firm of Hans Thoma, of Munich, with which electro-cardiograms have been taken. The loop or moving system consists of platinum wire 0·0025 mm. in diameter suspended from a glass hook, the tension being given by a small spiral spring, the system being mounted between the poles of a powerful electromagnet. The mirror mounted across the strips is 0·25 sq. mm. in area. It is stated that the instrument gives a sensitivity of 1 mm. on the photograph for 2×10^{-8} amperes. If such is the case the sensitivity is quite sufficient for electro-cardiograph work. The author is not in a position to state whether the periodic time is sufficiently short to satisfy the requirement that a deflection of 10 mm. for 1 millivolt must take place without overshooting in 0·02 second (see page 22).

The magnitude of this current varies continually during the systole of the heart. It has been found that in the majority of healthy people the heart passes through a normal cycle and thus gives practically the same electrical potential at every stage of the cycle.* If, therefore, the position of the galvanometer string is continuously photographed the potential corresponding to any particular heart movement can be determined. During the taking of the record the resistance of the galvanometer string and the body of the patient remain practically constant, and since the period of the string is so small (about 0·04 second) and the motion is nearly aperiodic, the movements recorded are a direct measure of the electromotive force at any instant. The maximum changes in electromotive force throughout the whole of the heart movement rarely exceed 3 millivolts.

The essential feature of the string galvanometer is the conducting string which forms the moving part of the galvanometer. This string is a quartz or glass thread, from 0·003 to 0·005 mm. diameter, on which a thin metallic coating of silver or platinum has been deposited. The string (S) is stretched between the poles of a powerful electromagnet N S, shown diagrammatically in Fig. 1, and an optical system E F A

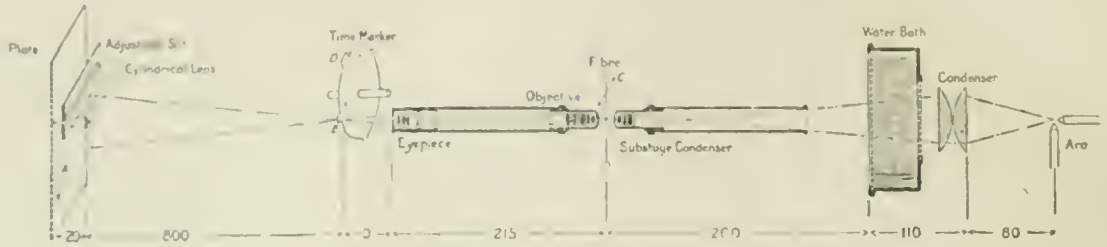

FIG. 2.—Optical system.

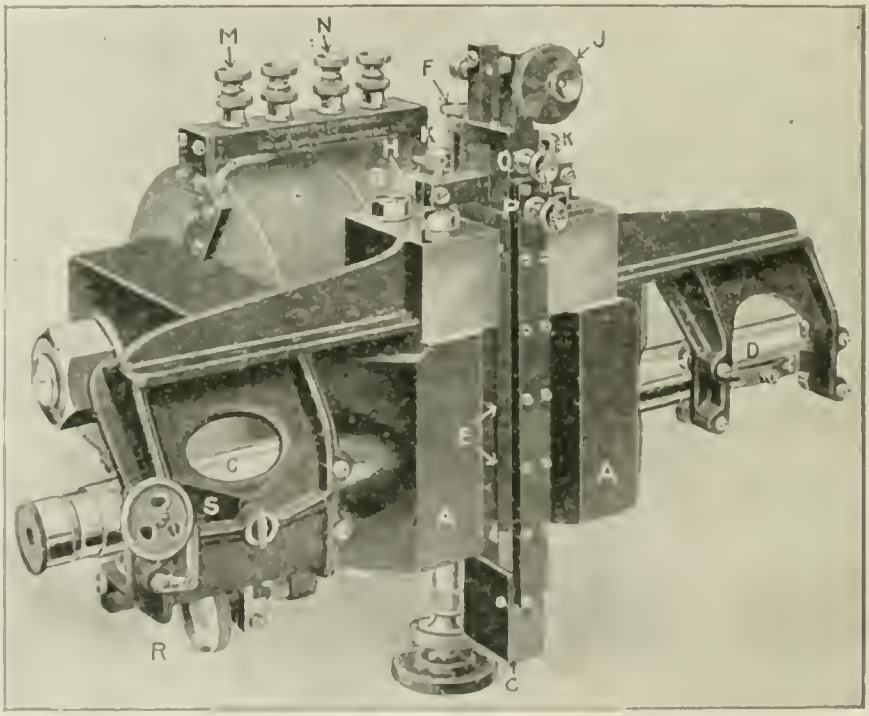

FIG. 3.—String galvanometer.

projects a shadow of the moving string on to a photographic plate.

When a current passes down the string the latter is deflected in the direction of the lowest arrow, i.e. at right angles to the magnetic field. If the direction of the current is reversed, the string will move in the opposite direction. Within the limits of the experiment the deflections of the string are directly proportional to

* In Lewis's study of the electrocardiograms of 50 individuals, showed that in 42 of these the records were almost exactly similar and was able to show that in ordinary physical examination six of the cases not included in the 42 would have been grouped as abnormal. T. Lewis and M. D. D. Gerrard, "The Human Electrocardiogram: a preliminary investigation of some new aspects in the study of cases of pathological study," *Philosophical Transactions*, 1911, 198, 201, p. 350.

the magnetic field and the current passing through the string, and inversely proportional to the tension on the string. The movements of the string are exceedingly small; a string about 100 mm. long, 0·003 mm. in diameter, and having a resistance of about 3,000 ohms in series with a patient having an approximate resistance of 4,000 ohms, moves through approximately 0·05 mm. when a potential of 3 millivolts is applied to it. A high magnification must therefore be used to study the detailed movements of the string.

Fig. 2 shows the optical arrangement diagrammatically, the distances being given in millimetres. The string is illuminated from the positive crater of an arc lamp, the light being concentrated by the condensers. A water bath is interposed as a screen opaque to heat rays to protect the sub-stage condenser and to prevent heating of the string. The field of the objective is projected on to the cylindrical lens, which focuses part of this into an intensely bright band of light on the photographic plate. The string appears on the front of the cylindrical lens as a long vertical shadow about 2 mm. wide, the part falling upon the cylindrical lens becoming a dark spot in the band of light projected on to the photographic plate. The magnification generally employed is 600 diameters. If the photographic plate or paper is given a motion at right angles to the axis of the cylindrical lens, e.g. in the direction of the arrow A, the whole length will be exposed except that portion which is covered by the shadow of the string. The movements of the string are parallel to the axis of the cylindrical lens, and as the instantaneous position of the string is indicated by an unexposed spot, a continuous record of these positions is formed on the moving plate. An adjustable slit is placed between the cylindrical lens and the plate in order that the maximum of detail consistent with good illumination may be obtained.

In order that the curves might be rapidly measured, Einthoven introduced a simple and excellent method of automatically photographing a scale upon his photographs. Lines are engraved on the cylindrical lens across its width to throw shadows on the photographic plate, appearing as well-defined lines ruled 1 mm. apart throughout the length of the record. This system of lines gives a scale of current in the galvanometer, or of the potential of the heart. A system of lines at right angles to the former ones are produced by interrupting the focused beam of light at B so that for a short interval no light falls on the plate as it travels past the slit, and in consequence a sharp line appears on the record. This system of lines gives a scale of time. The method of producing these lines at known and definite intervals of time will be explained later.

The equipment required to obtain an electro-cardiogram is as follows:—

(1) The galvanometer which receives the electrical impulses of the heart.
(2) The camera to record the movements of the string in the galvanometer.
(3) A time-marker or mechanism for marking time intervals on the photographic plate.
(4) A source of illumination by means of which the photographs are obtained.
(5) The electrical equipment for making the necessary standardization and other adjustments.
(6) The electrodes for making electrical connection to the patient.

It will be advisable to discuss the various types of instruments that have been devised under the above

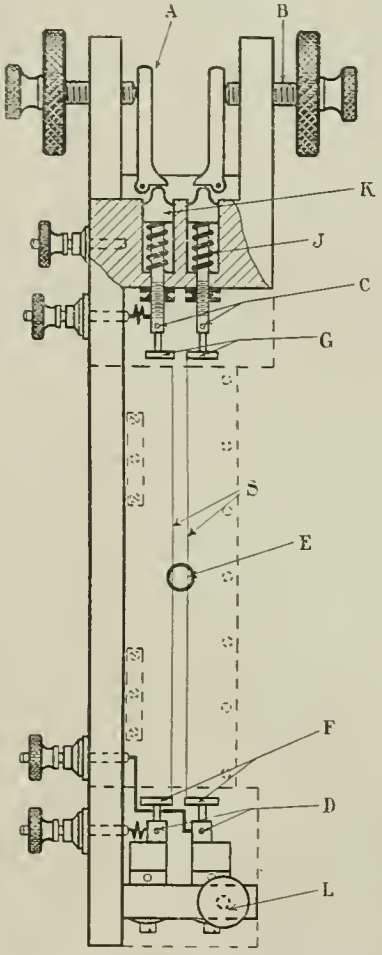

FIG. 4.—Fibre case for two-string galvanometer.

headings, finally dealing with one type of complete outfit:

Galvanometer.—Since the invention of the string galvanometer by Einthoven several models have been devised, although they all have the same general characteristics and are modifications in detail only. Einthoven's instrument, generally referred to as the Leyden model, has an exceedingly powerful magnetic field, 26,000 gauss. In order to avoid any probable ill-effects from the heating of the instrument by the current passing through the magnetizing coils, it was fitted with cooling coils of tubing through which water could be passed during an experiment. Edelmann, a Munich

manufacturer, slightly modified the model * and in a test of one of his instruments a field strength of 18,000 gauss was given for an expenditure of 160 watts on the field coils. The drawback to the original Einthoven and Edelmann models was the difficulty in making the chamber in which the string is situated air tight. A very small air current is sufficient to disturb the string when it is under the slight tension required for electro-cardiograph work. In addition to this it was not easy to replace the string if it were broken during an experiment, or if it were desired to insert one having different physical qualities.

A great deal of thought has been devoted to the development of models to overcome these drawbacks and also to decrease the weight of the original instrument. The most successful model is, the author believes, that designed by the late W. Duddell in 1905 for the Cambridge Scientific Instrument Company (see Fig. 3). In it the string is enclosed in an air-tight chamber generally referred to as the "fibre case." The chamber being air-tight the string is unaffected by draughts, dust which would otherwise collect upon it is excluded, and it is provided with mechanical protection. A milled head J is fitted to the fibre case and allows accurate adjustment of the tension and sensitivity of the string. A safety stop is also fitted to prevent the overstraining and hence the breaking of the string. The fibre case is geometrically supported on the three points H, L, L, and is held in position by the screw and anti-backlash spring F. The screw F also acts as an adjustment by means of which the string can be brought into the centre of the optical system.

Being held geometrically, the case can be removed after the completion of an experiment, with the certainty that it may be replaced in the correct position without re-adjustment. This is a useful feature, for if a second fibre case is adjusted ready to be put in position it can be easily substituted for the other in an emergency. With care a string will last for many years.

The magnet coil is generally wound in two sections and by arranging these in series or in parallel the galvanometer can be excited on either of two voltages, the standard windings being for 110 and 220 volts respectively for use on a lighting circuit, or 10 and 20 volts when accumulators are employed. As the steel pole-pieces of the galvanometer are practically saturated, variations in the voltage of the magnetizing current of ±5 per cent make little difference to the magnetic flux in the air gap (Gauss gauge) and hence to the galvanometer sensitivity. If, however, the supply voltage is subject to sudden fluctuations, it is advisable to use accumulators, as sudden variations in the field distort the electro-cardiograms owing to the mutual induction between the field magnet and the galvanometer circuit. The optical system consists of a small-diameter substage

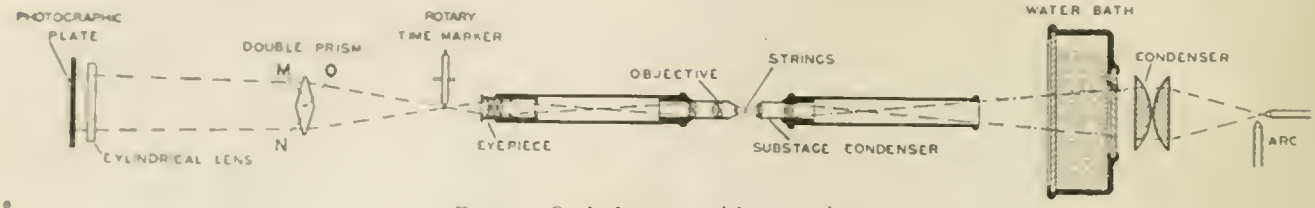

FIG. 5.—Optical system with two strings.

condenser (A A, Achromat) and an objective (Apochromat) and a compensating eye-piece (No. 12) which is employed as a projection lens. The normal magnification of 600 is obtained when the distance between the eye-piece on the galvanometer and the camera is 82·9 cm.

By a modification due to Apthorpe two strings may be employed simultaneously.* The two strings S are mounted in a case, 0·5 mm. apart, and are fitted with independent micrometer screws A and B (see Fig. 4) for adjusting the tension on each. The strings are entirely enclosed in a thin metal case (shown dotted), and a small mica window E allows the movements to

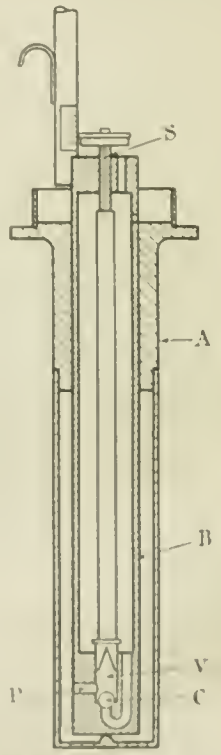

FIG. 6.—Section of cylinder.

* W. H. APTHORPE, "Note on an Improvement in the Einthoven String Galvanometer," *Proceedings of the Physical Society of London*, 1914, vol. 26, p. 314.

be observed at the centre. The images of the two strings are projected on to the double prism M N (Fig. 5), from which the two beams converge on the photographic plate.

A model due to Professor G. F. Nicolai * is so arranged that as the holder containing the string is introduced into the gap of the electromagnet the protecting cover is automatically removed. The drawback to the arrangement appears to be the risk that the cover is apt to come off unexpectedly and the string become broken.

Dr. Horatio Williams of Columbia University, New York, has made an ingenious compromise of the Einthoven and Cambridge models. In his instrument † the string is readily inserted after a covering plate has been removed. It has the advantage that no mica window is between the string and the optical system. This is an advantage when an abnormally high-power magnification is required, but it has the drawback that it is rather more difficult to make the chamber air-tight.

The design of the electromagnet in the Williams' model is extremely good, a field strength of 20,000 gauss being given with an expenditure of 11 watts. This is primarily due to the small air-gap and the effective winding of the coils round the magnet. It has, however, the disadvantage of being heavy.

Camera.—The problem of moving a photographic plate or paper at a uniform speed is a difficult one, and one to which a great deal of thought has been devoted. The range of speed required in clinical electro-cardiograph work is not very great, i.e. zero to 35 cm. per second, but in many physiological researches speeds as high as 4 metres per second are used. At the former low velocities any want of uniformity in the motion of the plate or paper is shown in a "banding" effect on the photograph, which may mask the phenomenon which is being studied. At this speed very small defects in the mechanism will cause large variations in the rate of movement of the plate.

Einthoven in his camera, which is complicated, has obtained almost perfect uniformity of motion through a range of 0·5 mm. to 2 metres per second.*

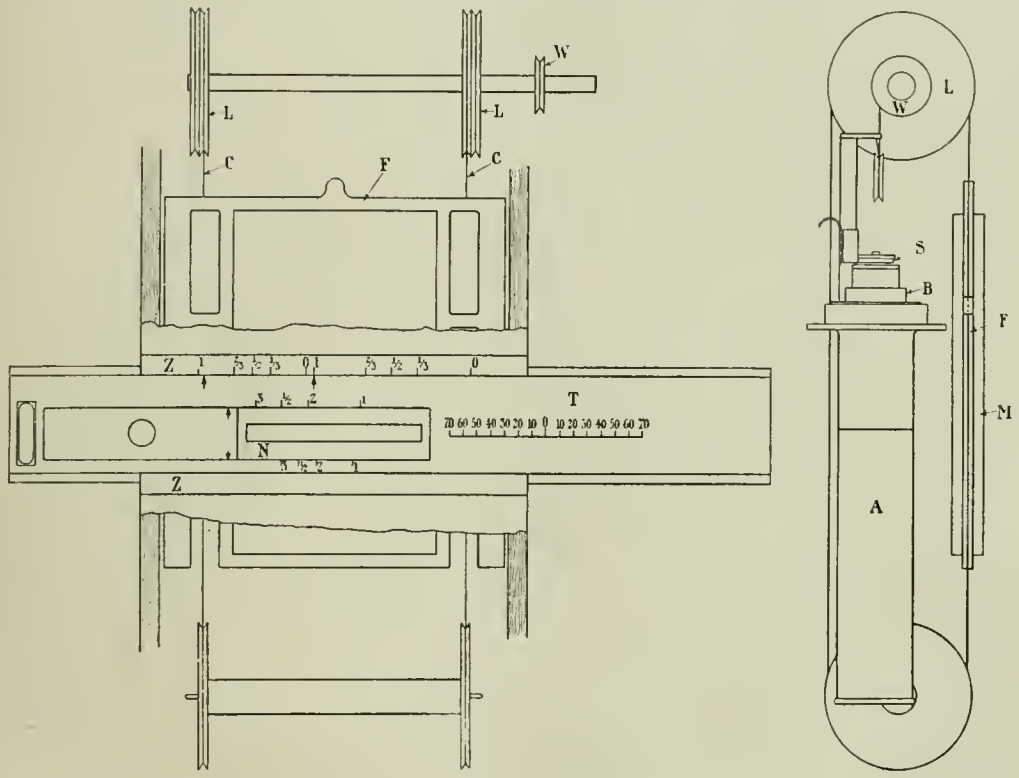

FIG. 7.—Falling-plate camera.

In the Cambridge camera, uniformity of movement is obtained by the use of a small hydraulic ram. A plunger B (see Figs. 6 and 7) accurately fits a cylinder A containing oil. In the plunger an adjustable valve V is fitted, through which the oil in the cylinder must pass as it is displaced by the falling plunger. The amount the valve is opened is controlled by a screw S fitted with a divided head.† The plunger is connected with a pulley W fixed on a shaft which passes through the camera box. To this shaft is also fixed

* Made by Huth, Berlin. † Made by C. F. Hindle, New York.

* W. EINTHOVEN: "Eine Vorrichtung zum Registriren der Ausschläge des Lippmann'schen Capillar-Elektrometers," *Archiv. für die ges. Physiologie*, 1900, vol. 79, p. 26.

† The author believes that the first application of an oil cylinder to control the movement of a photographic image is due to Sir Horace Darwin. In a photo-spectro-heliograph designed by him in 1902 for Sir Norman Lockyer, an oil cylinder was used to control the movement of a large carriage on which the optical system was mounted. This was moved by means of a falling weight, the rate of movement being controlled by an oil cylinder.

the top pair of pulleys L from which the frame F carrying the photographic dark slide M is supported. As the plate and carrier fall, the supporting cords C running over this pair of pulleys cause the shaft to revolve, and thus the movement of the plate is transmitted to the plunger B.

Since the pressure in the oil chamber due to the weight of plate and plunger is constant, the plunger can only move at a definite speed depending on the opening of the oil valve. The uncontrolled friction arising in the bearings and pulleys is exceedingly small in comparison with the controlled fluid friction through the valve, and thus the movement is extremely regular. The rate of movement of the plate can be varied by means of the oil valve from zero to 350 mm. per second. In order that time may be saved in the setting of the plunger, i.e. when lifting it into position, it is fitted with a non-return ball valve which allows the oil to pass quickly back into the cylinder without the necessity of altering the valve opening. This opening can therefore be set to give any desired speed, which can be repeated continuously without further attention. In the original design the plate and plunger moved in opposite directions in reference to the force of gravity; an improvement now adopted makes these movements in the same direction and so improves the control, and enables higher speeds to be obtained from the same weight of plunger.

The photographic plate is carried in a roller dark slide M, which can be opened when in position in the camera.

By means of a device suggested by Dr. Avery Newton any part of the width of the plate may be exposed. This enables several photographs to be taken on one plate, and it is now customary to take the photograph from the three Leads I, II, and III (see p. 21) upon the same plate. Fig. 14 is a reproduction of such a record. The three cardiograms have been exposed successively one after the other.

To expose the plate in three equal parts the small slide N (Fig. 7) is set to the line $\frac{1}{3}$ engraved on the lower scale, and the large slide T is set on the upper scale to the $\frac{1}{3}$, $\frac{2}{3}$, and 1 line successively, the plate being exposed after each setting. Other fractions of the plate width can be used if desired. The string is moved so that its shadow falls into the new position for each photograph by means of the screw F (see Fig. 3).

Professor J. K. A. Wertheim-Salomonson has also used a hydraulic cylinder for obtaining uniformity of movement of the photographic plate.* The plate is mounted in a frame, running on three wheels between two rails, supported by a cord attached to the piston of the cylinder. The cylinder (see Fig. 8) is fitted with a by-pass containing a sensitive valve fitted with a graduated head. In operation, the glycerine with which the cylinder is filled passes through the by-pass as the piston rises. The rate of movement may be varied from 1 to 150 mm. per second. The advantage claimed for this arrangement is the fact that the valve may be opened widely and the apparatus quickly re-set,

* J. K. A. Wertheim-Salomonson: "Un nouvel électrocardiographe Rapid Intrapareil," *Archives Néerlandaises de Physiologie*, 1907, vol. i, p. 618.

and also that it is possible to alter the rate of speed a which a plate is falling during exposure by opening o closing the valve. It is doubtful whether this arrange ment of valve is so efficient as the non-return ball valve The valve has to be opened and then re-adjusted betwee every experiment. With the ball valve the pisto can be re-set for an experiment without any delay If some intermediate gear in the form of pulleys i introduced between the piston and the carrier, speed up to 600 mm. per second may be obtained.

M. Bull of the Institut Marey has invented an in genious camera on which records up to a speed of 1 metres per second can be obtained without difficulty It consists of a brass drum A (see Fig. 9) rotating o

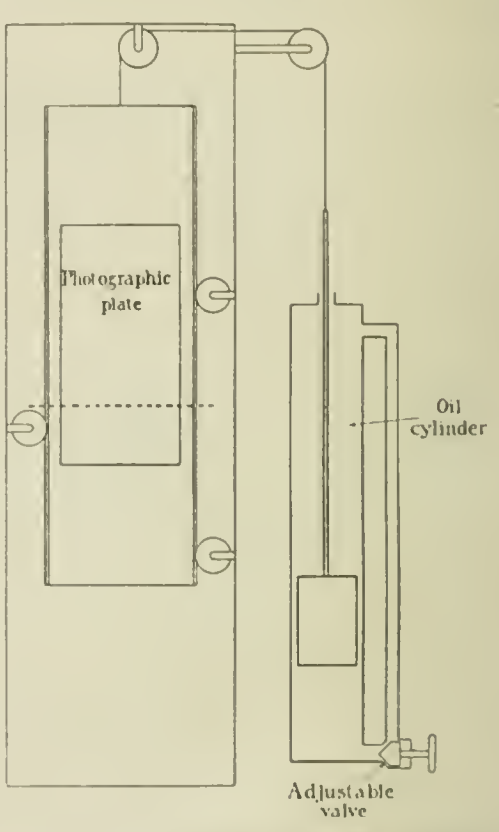

FIG. 8.—Section of cylinder in Prof. W. Salomonson's instrument.

a horizontal axis B in an octagonal case C, the uppe part of which may be opened for the purpose of insertin the photographic film. The drum has a diameter o approximately 33 cm. and carries a film or strip o sensitive paper about 1 metre long. The width o film used is generally 90 mm., but holding attachment are provided for taking films of 60 and 35 mm. in width The drum is rotated by means of a constant-speed motor driving through a pulley not shown in the figure By means of various sized pulleys and a reduction gear a large variety of speeds between 10 metres and 2·5 mm. per second may be obtained.

The motor is either fitted with a centrifugal governo which makes and breaks the actuating current, or i

is driven by a current controlled by a tuning fork. M. Bull was one of the first experimenters, if not the first, to use successfully the principle of the "phonic wheel" for controlling the speed of motors with a tuning fork fitted with a special form of contact breaker.* It must, however, be mentioned that it was invented by Lord Rayleigh in 1878.†

The shadow of the string is projected on the slit S behind which is a cylindrical lens L, in the focus of which the cylinder rotates. At the back of the slit two shutters are mounted, one of which—the safety shutter—is opened by pulling a small cord D. The second shutter is both opened and closed electrically by contacts F F carried on the drum axle. These contacts are so arranged that records of various lengths

Dr. Williams of Columbia University, New York, and the Cambridge Scientific Instrument Company, have also developed continuous-paper machines, although they are not quite so elaborate as some of the German models.

The construction of the Cambridge continuous-paper camera is shown in Fig. 10. The paper, which is 3¼ inches (83 mm). wide, is wound on the spool A and is drawn downwards behind the plate B by the rubber-faced friction roller C against which it is held by the loose roller D. The friction roller is mounted on the shaft carrying the driving pulley E and is driven by it. The paper is held in the focus of the cylindrical lens F by the pressure exerted by the plate B. After leaving the rollers C and D it passes through an opening

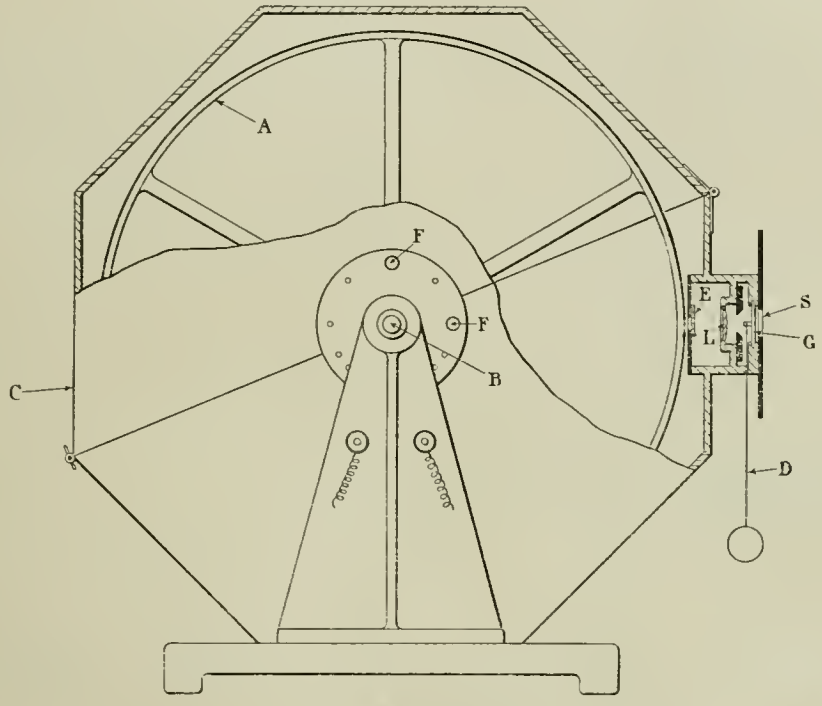

FIG. 9.—M. Bull's camera.

can be taken. In the standard instrument made by Boulitte of Paris, records of the following lengths can be taken as desired:—

8	records	12·5	cm. long
3	,,	33	,,
2	,,	50	,,
and 1	record	100	,,

The German makers of cardiographic apparatus have adopted continuous film or paper cameras as distinct from the photographic-plate type. The former has the advantage that records extending over several minutes can be taken if desired. In practice this is rarely wanted in clinical work.

* L. BULL: "Sur le mouvement des cylindres enregistreurs," *Extrait des Travaux de l'Association de l'Institut Marey*, 1910, vol. II.
† *Nature*, 23 May, 1878.

G in the base of the camera into a removable box underneath H. This box is completely closed, except for the opening J through which the paper enters and that through which it is withdrawn. The sliding shutters K and L are provided to close the opening in the bottom of the camera and the top of the removable box. A knife M operated from the outside can be drawn across the opening in the bottom of the camera to cut off the exposed length of paper. The paper is then taken in the removable box to the dark-room for development. Spare paper boxes are provided so that time is not lost during the absence of a box in the dark-room. The camera is driven by a motor, the speed being varied by changing the belt on the cone pulleys of the camera and motor. The motor is generally suspended on some form of anti-vibration table to prevent the vibration affecting the galvanometer. The design of this table

enables the length of driving belt to be easily adjusted, and hence it is possible with a pair of three cone driving pulleys of diameters a, ar, ar^3 to obtain seven speeds in geometrical progression corresponding to the ratios r^{-3}, r^{-2}, r^{-1}, r^0, r^1, r^2, r^3, viz. approximately 10, 15, 25, 35, 50, 75, and 115 mm. per second.

Dr. Williams' camera—made by C. F. Hindle of New York—is similar in all essentials except that the width of film (60 mm.) is slightly less than in the Cambridge

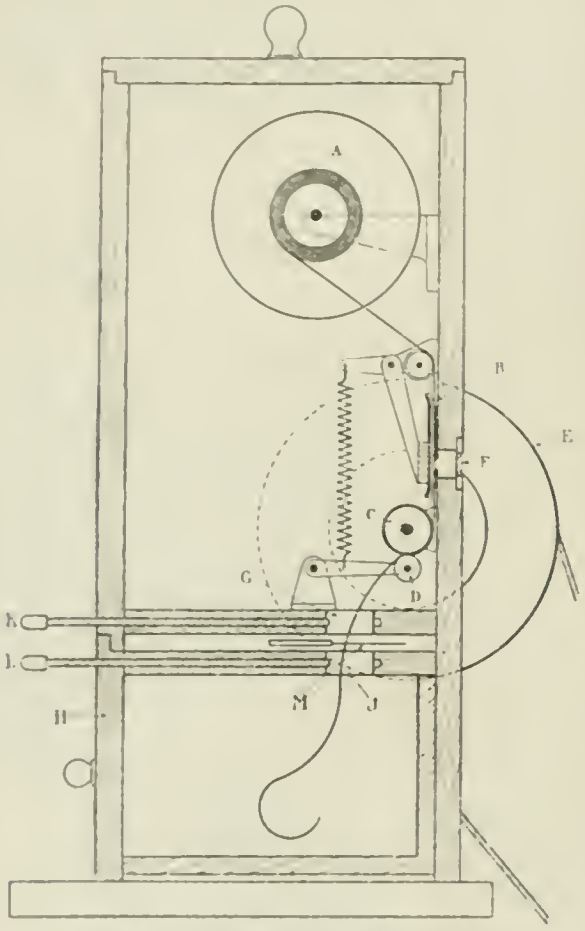

FIG. 10.—Continuous paper camera.

model. The camera itself is built of metal and not of wood. This is a distinct advantage when climatic conditions are unfavourable to wood.

The Nicolai or Hath instrument also uses film 60 mm. in width. Two models are in general use, one which is very similar to the cameras just described, and a second which is fitted with an automatic developing attachment by means of which the paper passes through developing and fixing baths, a developed record leaving the camera two minutes after it has been exposed.

Where a very large number of records are to be taken continuously, there is no advantage in having an automatic camera as it takes some little time to start up and requires a good deal of cleaning after use.

In practice it will be found that when a continuous record has been taken it rarely exceeds 250 cm. in length. It is best developed either by placing it emulsion side upwards on a board and moistening with the developer placed on a sponge, or by holding the ends in the two hands and drawing the paper vertically backwards and forwards through the developer.

Time-marker.—An essential condition for the study of the records obtained from the electro-cardiograph, and especially for the comparison of any two records or electro-cardiograms, is an accurate time scale. Einthoven at once recognized this and developed, in the masterly way in which the whole of his work has been carried out, an accurate, but complicated, mechanism for printing a time scale on his record simultaneously with the photographing of the electro-cardiogram.

A comparatively large electric motor drives, through accurately cut gearing, a sector wheel which intercepts the light beam from the galvanometer to the camera. The speed of the sector wheel is controlled by means of a standard clock. The mechanism is too complicated for the ordinary clinical laboratory, and other simpler pieces of mechanism have had to be devised. A vibrating reed in which the vibrations are maintained electrically is frequently employed. The shadow of the reed is projected on the photographic plate and

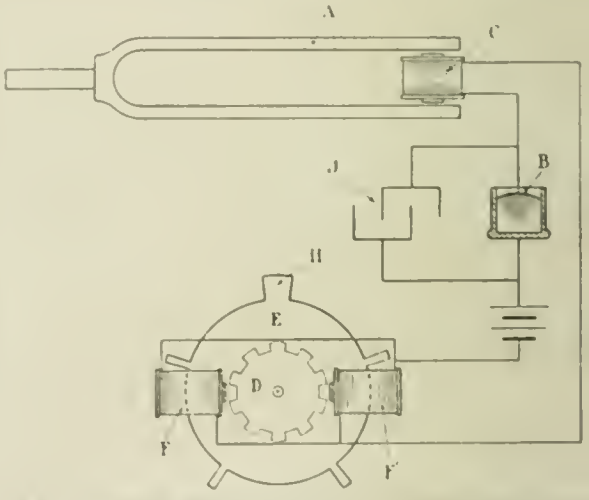

FIG. 11.—Electrically-maintained tuning-fork and motor.

record similar to Fig. 13 is obtained. In all the records in this figure the time-marker is indicating thirtieths of a second. Not infrequently the method is modified by using an electrically driven tuning-fork to maintain a small Deprez time-marker in motion. This is a convenient arrangement, as the tuning-fork can be placed on a rigid support at a little distance from the galvanometer and camera; the time-marker is placed so as to intercept the light beam.

A further modification of this latter method, which is largely due to M. Bull, is the one that has come into general use. An electrically-maintained tuning-fork or bar, A, of a frequency of 50 per second, makes and breaks at the contact B (see Fig. 11) a circuit in which are the field coils I and I' of a Rayleigh attracted-iron

motor. The coil C which maintains the tuning-fork in vibration is in the same circuit, so that the rotor of the motor simultaneously receives impulses with the fork.

The rotor D has 10 teeth and is therefore moved forward one complete revolution every 1/5 second. It is started by giving a gentle twist to the axle and, as soon as it has reached the correct speed, runs synchronously with the fork. The rotor carries a disc E mounted upon its axle, having five projecting pieces which, when interposed in the light beam leaving the eye-piece (see Fig. 2), occult it for a short interval of time, thus preventing the light from falling on the plate. These unexposed parts form the vertical time-lines shown in the cardiogram in Fig. 14. The fifth projecting piece H on the disc is made wider than the others and hence gives a wider and apparently darker line on the photograph. The lines shown are therefore 1/5 second and 1/25 second. By fitting discs having a greater number of teeth, and by making the photographic plate or paper move more rapidly, small intervals of time such as 0·001 second can be measured.*

A small condenser J (3 mfd.) must be placed across the contact to extinguish the sparks on the break. If a condenser is employed, a motor can be run continuously for days without any deterioration of the contacts.

* This statement must be accepted with a certain amount of reservation. It assumes that the tuning-fork is adjusted to an accuracy of at least 1 per cent, and that the positions of the teeth of the rotor and the spokes on the time-marking wheel are cut to the same degree of accuracy. It also assumes that the friction in the bearings of the rotor is constant, and that the magnetic impulses to the fork and motor are also constant. The intervals on the record, such as Fig. 14, are generally 1/25 second apart, but not infrequently the wheel is adjusted to give intervals of 1/100 second. In such cases measurements of 1 1,000 second are made by estimation.

Illuminant.—The most satisfactory source of light—especially if quick records are to be taken—is an arc lamp. A useful model—because the position of the crater remains practically constant—is one in which the positive carbon is mounted horizontally. The carbons are fed together automatically. In clinical work the current required does not generally exceed 6 amperes. In some of the German instruments Nernst lamps are employed. It is now impossible to obtain Nernst lamps in this country and the "Pointolite" made by the Ediswan Company is from many points of view a better lamp. Not improbably it will become the lamp used in clinical electro-cardiographic work.

Electrical connections.—As previously mentioned, connection is made to the patient by means of non-polariz-

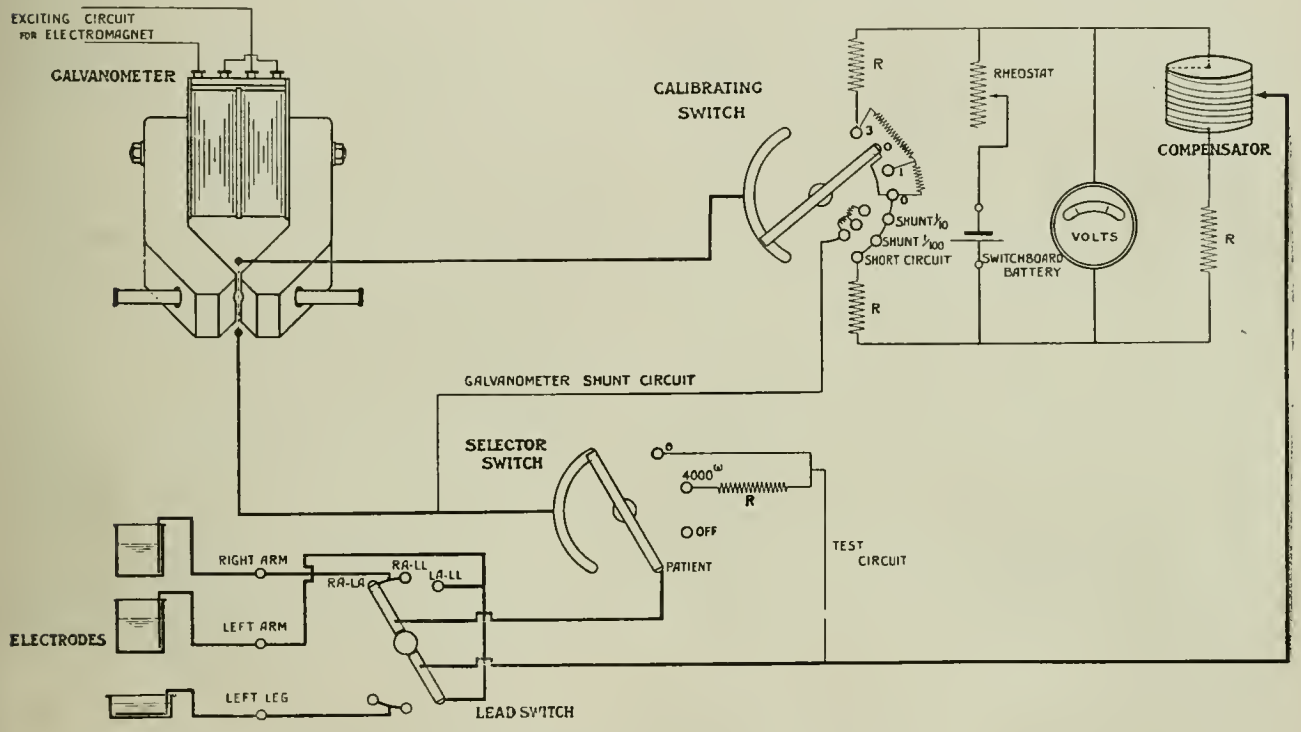

FIG. 12.—Diagram showing connections of switchboard.

able electrodes into which the limbs of the patient are placed. Three electro-cardiograms are taken, generally on the same photographic plate, the two arms and the left leg being used. Following the notation of Einthoven the connections are always referred to as follows:—

Lead I. Right arm and left arm connected to the instrument.
II. Right arm and left leg.
III. Left arm and left leg.

Superimposed on the varying currents due directly to the heart, there is generally a relatively large and fairly steady current due to an electromotive force set up by the glandular activities of the skin and known as "the skin current."

It is necessary that this should be neutralized by

the introduction of an equal and opposing potential difference.

In order that the various cardiograms may be comparable with each other, it is essential that the galvanometer from which they are obtained should be standardized to the same sensitivity. In this, all observers have followed Einthoven's lead and have adopted a sensitivity of an excursion of 10 mm on the photographic plate for an applied potential difference of 1 millivolt when the connections are complete through the patient. It is also frequently desirable to know the resistance of the galvanometer and of the patient. The electrical connections to fulfil the above requirements have now after a lengthy evolution been reduced to a not very complicated design and are shown in Fig. 12.

An accumulator or large dry cell supplies the current for the potentiometer circuit. The electrodes in which the patient's limbs are placed are connected to the three terminals on the control board, and assuming that it is desired to take a cardiogram of Lead I—right arm, left arm—the lead switch is placed as in the diagram.* In all preliminary work with the string galvanometer it is advisable to cut the galvanometer out of the circuit by placing the calibrating switch in the "short-circuit" position. The current in the circuit is then adjusted by means of the rheostat until the pointer of the small voltmeter indicates 0·5 volt. When such is the case there is a drop of 1 millivolt and 3 millivolts respectively across the studs of the calibrating switch where marked 1 and 3. The calibrating switch is then moved to the position shunt 1/100, when 1/100th of the current passes through the galvanometer. A deflection on the galvanometer due to the skin current of the patient will then be observed. This is brought to zero or "compensated" by the introduction of a counter electromotive force, the rheostat or "compensator" being turned until there is no deflection of the galvanometer. The switch is then moved to 1/10, which will probably produce another deflection, which must again be neutralized by the rotating compensator. The switch is finally put on to the zero position, and, if necessary, the compensator is again adjusted. The galvanometer will then show the periodic deflections due to the electromotive force produced by the heart's action.

The galvanometer should now be calibrated and, if necessary, adjusted for sensitivity. As previously explained, it is usual that the image of the fibre should be deflected through 10 mm. for a change in electromotive force of 1 millivolt. The mean position of the string is carefully observed and the calibrating switch put on to the "1" stud. This introduces 1 millivolt into the circuit, and the shadow of the string will move to a point on the scale depending on the slackness of the fibre. The tension on the string is adjusted by means of the micrometer screw until the correct sensitivity is obtained. If a larger deflection is required, 3 millivolts may be introduced by putting the switch on the "3" stud, and a deflection of 30 mm. should be given.

* The operation of standardizing an instrument is shown graphically in Fig. 5, p. 8, of 'Clinical Electrocardiography,' by Dr. Thomas Lewis (Messrs. Shaw & Sons). It is a reproduction of a photographic record of the tests made when carrying out the above operations. The first chapter in this book gives very clear directions as to the necessary electrical adjustments required to obtain satisfactory cardiograms.

The resistance of the string is readily measured. The calibrating switch is placed on the "short-circuit" position and the selector switch on the zero position. The compensator is then adjusted until the galvanometer string remains at zero, when the calibrating switch is moved from the "short-circuit" to "O" position (the shunt positions having been used for safety). The galvanometer is adjusted to standard sensitivity for 3 millivolts. The 4,000-ohm resistance

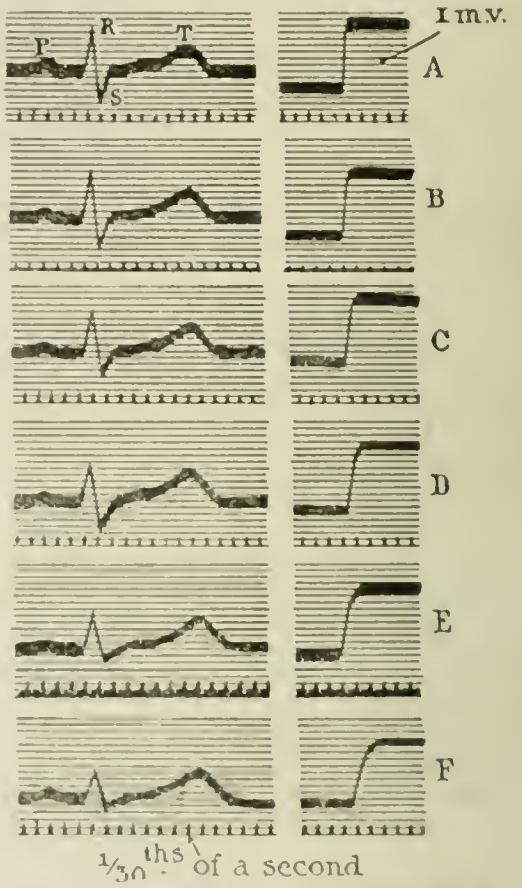

Fig. 13.—Illustrating the effect of varying the tension of the string of the galvanometer.

is introduced by moving the selector switch, and the deflection in mm. then observed.

$$\text{The resistance of the fibre} = \frac{4{,}000 \times \text{2nd deflection}}{30 - \text{2nd deflection}}.$$

In a newly silvered fibre the resistance varies from 2,000 to 6,000 ohms, and usually slowly increases.

The resistance of the patient may be determined in a similar manner. First compensate for any skin current and calibrate the galvanometer to standard sensibility, viz. 30 mm deflection for 3 millivolts. The patient is then disconnected by moving the selector switch to the 4,000 position, and the "compensator" adjusted until the string remains at its zero position. The deflection when 3 millivolts are introduced is then noted. Knowing the resistance of the galvanometer string, that of the patient may be determined, the deflections being proportional to the resistance

of the galvanometer string and the patient, and the galvanometer string and 4,000 ohms respectively. The resistance includes that of the electrodes.

Many of the heart movements it is desired to study are very rapid, and experience has shown it is essential that the string when adjusted to the working sensitivity of 10 mm. per millivolt should be just aperiodic. Corresponding to this sensitivity a certain tension is required in each string. This gives each string a certain free period; the damping at this period must be such that the motion is aperiodic.

In practice it is found that a silvered glass or quartz fibre about 100 mm. long and 0·003 mm. in diameter well fulfils the conditions and attains practically its full deflection corresponding to the applied voltage in less than 0·02 second. Fig. 13* shows the effect of varying the tension on the string in a striking manner. The curves on the right of the figure were taken with different resistances in circuit and they were all adjusted to a sensibility of 10 mm. per millivolt with different tensions on the string. From above downwards (A to F), the added resistance was increased and the string slackened. The deflection times for the six strings were 0·013, 0·023, 0·028, 0·045, 0·060, and 0·070 second. Since the damping factor is a constant, a reduction in the tension on the string causes overdamping, and hence the string cannot follow the changes in potential due to the heart's action with sufficient rapidity and the curves are distorted. This is clearly shown in the records to the left of the figure. The electro-cardiograms of the first two strings are practically alike and correct; distortion is seen in the third record when the deflection time is increased to 0·028 second.

The electrodes used are of the non-polarizable immersion type. They consist of an inner porous vessel which is filled with a 20 per cent saline solution and an outer stoneware vessel filled with a saturated zinc-sulphate solution and containing an electrode of zinc. Lewis has shown that records taken with polarizable electrodes are distorted, and although the amount by which they are distorted is slight it is inadvisable to use them.* If the electrodes polarize slowly, distortion is present: if they polarize rapidly, distortion is greater. Distortion is due to the rapid development and maintenance of a charge on the surface of the electrodes while current is flowing through them. The electrodes are connected by flexible leads to the switch-board of the instrument.† Fig. 14 is a reproduction of an electro-cardiogram obtained from the three leads. The various phases in the curves have been lettered according to the notation of Einthoven. P, the first phase, is due to the simultaneous contraction of the two auricles. Q, R, S, and T (of which R and T are the most prominent) are the result of simultaneous contraction of the two ventricles.

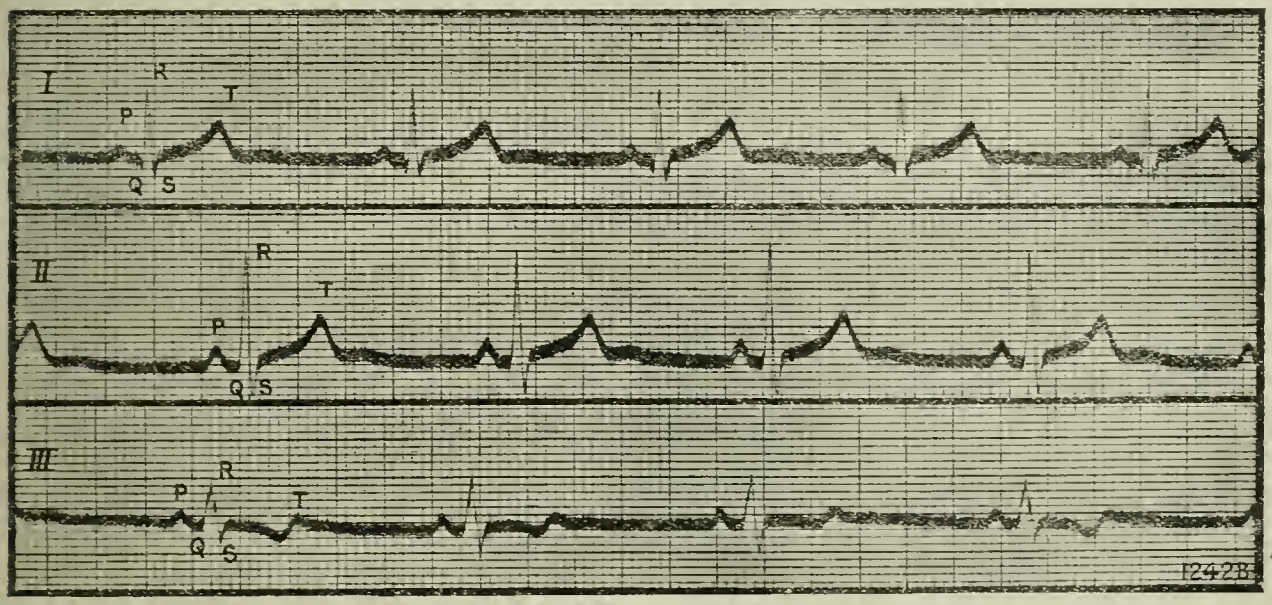

FIG. 14.—Actual cardiogram.

As with all apparatus designed for research work, extreme opinions as to its value must be received with caution. On the one hand the enthusiast is inclined to claim too much for the new tool with which he is doing such good work, whilst the man of conservative instinct is apt to depreciate new and complicated instruments. It is not an easy matter to get the best out of such apparatus, some special training and experience in its use being essential.

* Reproduced by kind permission of Dr. T. Lewis from Fig. 6 of "Clinical Electro-cardiography."

* T. LEWIS: "Polarizable as against non-polarizable electrodes," *Journal of Physiology*, 1915, vol. 49.

† If desired, the patient may be several hundred yards from the instrument, the limbs being placed in electrodes at the bedside. In some hospitals the wards are electrically connected to the electro-cardiograph room by cables and telephones, so that the record of a patient in bed may be taken in the laboratory with as little inconvenience as possible to the patient (W. EINTHOVEN: "Le télé-cardiogramme," *Archiv internationale des Physiologie*, 1906, vol. 4, p. 132).

The electro-cardiograph has already brought to light new facts, has afforded a solution of conditions and physical signs hitherto difficult of explanation. I understand that with its aid the young clinician may obtain results hitherto gained only by long and careful observation and after wide experience, while the experienced physician on the other hand may widen the field of his observation, control his results and thus strengthen his diagnosis.

That an instrument of great interest from the point of view of the physicist, both in its design and in its achievements, should have become so important to clinical medicine is only another example of the interdependence of the sciences.

The thanks of the author are due to Dr. T. Lewis, F.R.S., Professor Sims Woodhead, and also to his colleagues Mr. C. C. Mason, Mr. W. H. Apthorpe, and Mr. F. Rowcliffe, for many valuable suggestions and criticisms.

APPENDIX.

Technical Data.

Temperature coefficient.—The string galvanometer has undoubtedly a considerable temperature coefficient, especially at the point where the string is stretched exactly vertical without torsion or tension. The string is held in a metal frame and this is sensitive to temperature changes. The temperature coefficient of fused quartz is $0{\cdot}4 \times 10^{-6}$, whilst the value for brass is 18×10^{-6}. The metal has therefore a temperature coefficient of about 40 times that of the quartz. The result is that with an increase in temperature the string is stretched and the deflection for a given current is reduced.* Metallic wires having a greater temperature coefficient than quartz or glass are not so troublesome in this respect. Experiments made by the Cambridge Scientific Instrument Company with a quartz and also with a bi-metallic support to eliminate this temperature effect on the thread were not successful. In practice it will be found that after the instrument has been running for one or two hours the temperature remains remarkably constant and that little trouble is caused by variations in temperature. It is, however, advisable to adjust the instrument to a definite sensitivity by altering the tension on the string before making any observation.

Quartz or glass fibre.—The quartz fibres are generally drawn by the method suggested by C. V. Boys* and are silvered by means of the silver nitrate and Rochelle salt process.†

A method due to Suter in which a falling weight draws a glass thread through an electric heater has proved very successful in the manufacture of glass fibres. The latter appear to silver more easily than the quartz. Cleanliness is essential for the successful silvering of either glass or quartz fibres. If possible a fibre should be drawn and then silvered almost immediately. It appears to be impossible chemically to remove the film that is deposited on a fibre in a few hours even in a comparatively clean room. If the most stringent precautions are taken against dirt, and pure chemicals are employed, little difficulty will be experienced in the manufacture of satisfactorily conducting fibres.

A silvered fibre 75 mm. long and 0·003 mm. in diameter has an approximate resistance of 2,500 ohms. When first silvered it will not improbably have a resistance of 2,000 ohms, and this will gradually rise to about 2,500 ohms. It will then remain constant over many

Sensitivities and Resistances of Some String Galvanometers (Cambridge pattern) fitted with Strings of Various Materials. Magnification—600 diameters.

Material of Fibre	Diameter	Resistance	Period	Deflection in mm. per Micro-amp.	1 mm. Deflection produced by
	mm.	Ohms	Second	mm.	Micro-amps.
Silvered glass	0·003	8,720	0·004	7·3	0·137
,, ...	0·002	6,010	—†	68,400	0·000015
,, ...	0·0035	3,060	—†	48,000	0·000021
			0·005	13·2	0·076
,, ...	0·0025	12,030	—†	67,000	0·000015
,, ...	0·0025*	4,000*	—	40*	0·025
Aluminium wire	0·035	6·9	0·030	13·2	0·076
			0·0012	0·013	76
Silver wire	0·017	8·2	0·082	43	0·023
			0·0026	0·048	21
Platinum-silver wire ..	0·012	230	0·021	4	0·25
Copper wire	0·015	6·3	0·016	2·5	0·4

* These values correspond to the values used for cardiographic work.
† In this case the movement of the fibre was quite dead-beat; it took about 10 seconds to attain its full deflection.

* In the position mentioned above, Einthoven has shown that it is desirable to control the temperature of the instrument to 0·05 degree C. W. Einthoven: "Die Konstruktion des Saitengalvanometers," p. 303.

* C. V. Boys. "On the Production, Properties, and some Suggested Uses of the Finest Threads," *Philosophical Magazine*, 1887, vol. 23, p. 489. R. Threlfall: "On Laboratory Arts," pp. 204–9; Macmillan & Co., London.
† "On Laboratory Arts," p. 131.

months, assuming its tension is not varied through any large amount and that the maximum tension is not employed.

Both Einthoven and Williams * have introduced the method of silvering or platinizing the fibres by the cathode spray. The film so deposited is more homogeneous and smooth than any chemically deposited film. It has the advantage that as the film is so thin no appreciable increase in air damping is introduced, as must occur in the thicker chemically deposited film. The image of a fibre covered in this way is also much cleaner when projected on to the slit of the camera. Williams has calculated that a film deposited by the cathode spray is 48×10^{-6} mm. in thickness. The sprayed films gradually rise in resistance, as the following figures show :—

December 1913		August 1914
2,400 ohms	rose to	3,420 ohms
3,020 ,,	,,	3,820 ,,

Einthoven has studied in detail the theoretical considerations of the mass of the string, air-damping, resistance, etc., and reference should be made to his papers on the subject.

The following data with regard to the galvanometer and accessories used in electro-cardiograph work may be of interest :—

Field magnet of galvanometer.

Standard winding I.

Exciting voltage for coils connected in series = 220 volts.

Exciting voltage for coils connected in parallel = 110 volts.

Normal exciting current, coils in series = 0·3 ampere.

Normal exciting current, coils in parallel = 0·6 ampere.

Standard winding II (for accumulator circuits).

Exciting voltage for coils connected in series = 20 volts.

Exciting voltage for coils connected in parallel = 10 volts.

Normal exciting current, coils in series = 3 amperes approx.

Normal exciting current, coils in parallel = 6 amperes approx.

Energy absorbed in coils in series or parallel = 60 watts approx.

Fibre or string.

When the vibrating fibre is adjusted so as to deflect 10 mm. per millivolt, the magnification being 600, the deflection time = 0·016 second.

Length of fibre = 100 mm.

Resistance from 2,000 to 8,000 ohms, usually about 4,000 ohms.

Diameter of fibre (silvered) = 0·002 to 0·0035 mm.

Arc lantern.

Size of carbons. Positive and negative carbons = 9 mm. diameter. Length of positive carbon twice that of negative carbon, being respectively 200 mm. and 100 mm.

Normal current = 6 amperes.

Resistance required in series with arc on 100 to 110 volts = 9 ohms ; 200 to 220 volts = 25 ohms.

Optical work in galvanometer.

Small-diameter substage condenser A A Achromat, external diameter = 12 mm.

Objective. Apochromat, external diameter = 12 mm.

Compensating eye-piece, No. 12.

Microscope hole in magnet = 13·5 mm. diameter.

Normal magnification of 600 when distance between eye-piece on galvanometer and camera plate = 32·5 in. (82·5 cm.).

Plate camera.

The dark slides are fitted with an adaptor to take the following sizes of plates :—

(1) $6\frac{3}{4}$ in. by $3\frac{1}{4}$ in.—" Stereoscopic size."
(2) $7\frac{1}{2}$ in. by 5 in.
(3) 17 cm. by 8·5 cm.
(4) 18 cm. by 13 cm.

Speed of plate can be varied between zero and 350 mm. per second by means of the oil cylinder valve-adjustment.

Paper camera.

Bromide paper = $3\frac{1}{4}$ in. wide, in lengths of 75 yards.

Possible speeds of paper with motor running under normal conditions and on correct voltage = 10, 15, 25, 35, 50, 75, and 120 mm. per second.

Time-markers. Vibratory pattern.

No. 1 period, 0·08 second ; time divisions, 0·04 second (1/25 in.).

No. 2 period, 0·04 second ; time divisions, 0·02 second (1/50 in.).

Will operate on 1 dry cell.

Rotary pattern.

Speed of time wheel = 5 revolutions per second.

Time wheel No. 1.

Projections on wheel arranged to give :—

Main divisions of time = 0·2 second (1/5 in.).

Intermediate divisions of time = 0·04 second (1/25 in.).

Time wheel No. 2.

Main divisions of time = 0·1 second (1/10 in.).

Intermediate divisions of time = 0·02 second (1/50 in.).

Voltage required for motor and vibrating bar = 4 volts ; current = 0·45 amp.

Vibrating bar = 50 periods per second.

Condenser = 3 microfarads.

Cardiograph control board.

Voltages used for standardizing the deflections of the galvanometer = 1, 2, and 3 millivolts respectively.

Range of skin current compensation possible = 0 to 200 millivolts, positive or negative.

Normal range of resistance measurement = 0 to 5,200 ohms.

* H. B. Williams : " On the Silvering of Quartz Fibres by the Cathode Spray," *Physical Review*, vol. 4, p. 517.

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H. B. Williams: "On the Silvering of Quartz Fibres by the Cathode Spray," *Physical Review*, 1914, vol. 55, p. 517.

Discussion.

Dr. T. Lewis: It was my privilege some 10 years ago to introduce to clinical medicine in this country the electro-cardiograph. The first instrument I used was the Edelmann instrument; but it is to be regarded now as a relatively clumsy machine. While working on that machine I had the good fortune to meet the author, and during the last 8 years my laboratory at University College has worked in active co-operation with his firm. I would very strongly endorse Professor Woodhead's remarks regarding the need of co-operation in every branch. The apparatus which the author has shown this evening is essentially a clinical installation; it is set up for clinical purposes, and very many of the adjustments in the arrangement of the different pieces of the apparatus and in the switchboard have come as a direct result of the co-operation between the two laboratories. The instrument as it now stands is very speedy in taking accurate records. When I mention that three curves may be taken from a patient's heart within a few minutes, whereas in the old days it would have taken us perhaps half an hour to secure the same curves, it will be seen at once what the medical profession has gained through such an adjustment. I should like to show a few clinical records and say a few words in relation to the interpretation of the curves as they are taken from patients, and to illustrate the value of such apparatus to us as clinicians. I will take one cycle of a heart beat. Each beat of the heart sets up a complex series of deflections of the string. The heart consists of two parts, the auricular and the ventricular portions, and each of these gives rise to an electric current in the body, which is registered by this apparatus, so that any derangement of the heart's action can be observed. [Dr. Lewis then showed a number of lantern slides.] Lastly I will show a few records of heart sounds obtained with this machine; by connecting the string of the galvanometer to a microphonic system, we are able to obtain records of the heart's sounds. The microphone which has been available so far is not satisfactory; we want a microphone with a higher natural frequency, one which will record oscillations of, say, 300 to 400 or even 500 per second. If we could obtain such a microphone and work it in conjunction with a galvanometer we should be able to record a good many sounds from the heart which are at the present time quite unobtainable.

Dr. Sidney Russ: There are two questions which I should like to put, but I am not sure whether I should address them to the author or to Dr. Lewis. Looking at some of the tracings obtained by means of the machine, one notices there is often a series of what seem to be mechanical vibrations. They appear to have quite a different periodicity, and sometimes they give a lot of trouble. I should like to know whether they are

entirely due to mechanical vibrations, or whether there is any physiological basis for them. In the second place, in the apparently quiescent part of the curve it may be noticed that occasionally the curve rises ; sometimes it gives a slight rise and then falls back to its previous level. It seems unlikely that that would be a skin-current effect due to incorrect compensation, and it has been suggested that it may have a physiological basis. It is a very small effect, and the present sensitiveness of the instrument would not, perhaps, allow any actual conclusion upon it, and that raises the question as to whether, in looking for still smaller effects that are being studied to-day, it will be at all advantageous to cut down the skin resistance. In the paper, various estimates of the skin resistance are given between hand and hand, and there is rather a big margin allowed for it. The figures are 2,000, 3,000 and 5,000 ohms. I have no doubt the author knows of the experiments by Professor Gee on the resistance of the human body, and how it can be very considerably lessened by the preparation of the surface of the skin. I should like to ask him whether he thinks any useful purpose would be served by elaborating those particulars.

Dr. A. Blackhall-Morison : I fully endorse what Dr. Lewis stated in his concluding remarks as to the desirability for the invention, with the help of electrical engineers and experts, of some means of detecting, better than one can now, some of these sounds which as a rule elude our ears. There is no question that there are conditions of the heart which escape us, and which electrical methods have undoubtedly revealed, such as the condition that Dr. Lewis spoke of last, where the condition of rhythmical contraction of the auricle is too rapid and too fine to be heard. Is there any possibility of the time-marker being made absolutely automatic ? With the instrument I use, which is made by the Cambridge Scientific Instrument Company, it is sometimes necessary to revolve the rotor half a dozen times in order to catch the time of the tuning-fork. Would it be possible to arrange so that one could have a simultaneous result without the constant effort to find the mark ? The light I use is the one used here, and I find it is not always so satisfactory as it might be, although one takes the trouble to get the electrodes as nearly as possible into the correct position. If the automaticity of the rotor could be secured and also a little better illumination, I think the instrument would be perfect.

Dr. G. E. S. Ward : It may interest some of the members to hear my views from a clinical standpoint. I cannot praise too highly the apparatus which has been described by the author. I was present at University College Hospital when this particular type of apparatus was first installed, and I took a great deal of trouble to see that we got the same apparatus installed in the hospital to which I belong. Although it looks somewhat complicated to a novice, it really is extremely easy to work ; in fact, the various parts are so carefully put together that one might go further and say it is almost fool-proof. At the hospital where I work, every ward is wired to the apparatus and it is possible to take tracings from every bed in the hospital. In spite of that somewhat complicated system, however, we have never had any radical defect of the machine itself, although we have had a little trouble occasionally in connection with the wiring between the wards and the machine. Coming to the various parts, as regards the galvanometer and the time marker and the camera, I cannot praise them too highly. They have never caused any inconvenience or trouble at all ; but there are, in regard to other parts of the apparatus, one or two little points about which I should like to ask questions. When one realizes the consummate care which has been taken in the other parts of the apparatus, one cannot help feeling that if some means were adopted of covering in the compensating wire and sliding adjustment on the control board, defects due to microscopic pieces of dust would not arise. Then with regard to the electrodes, those shown are admirable, but there are certain types of patient who cannot sit in a chair ; they may be very ill and they must have their tracings taken from the bed. I cannot help feeling that if something could be bound round the limb it would be more comfortable, and therefore one would be more likely to get a more perfect record. If a patient is very nervous or restless owing to illness one is not likely to get as good a record as one might otherwise do. For some years the hospital to which I belong has been accustomed to use a different type of electrode, which might be condemned as not being non-polarizable, but experience has shown us we can get very good tracings. I have brought the inside of one of these electrodes. It is a piece of matting of copper filing and string and flexible. That is sewn into a flannel jacket long enough to encircle the limb. This is attached by an ordinary screw terminal to the machine. If this is kept thoroughly soaked in saline solution, and rubber sheeting is then wrapped round it so that it keeps moist, we have found by practical experience that we get very good tracings—better tracings than we had obtained sometimes from using the apparatus shown here. It is only a slight point, but I should like to hear the author's opinion on it. Finally, there is one point to which he refers on page 21, with regard to the light. It is most important to have as steady a light as possible, and I think that the light provided on the apparatus is as steady as an arc lamp can be. This week I asked Dr. Sidney Russ if it would be possible to work with a "Pointolite." We have not tried it yet, but we feel inclined to do so, because it gives a perfectly steady light.

Mr. P. M. Baker : Dr. Ward has mentioned the possible use of the "Pointolite." We tried it on some optical indicators of aero-engines and found it useless. I do not know why, and I have not since had time to investigate. We got very under-exposed photographs with the "Pointolite," whereas with a small arc of about the same candle-power we got beautiful ones.

Professor A. W. Porter : It does not seem to be generally known that an instrument for indicating electric currents by means of the movement of a fine thread or string between the poles of a magnet was devised by Cumming in 1826; and the gold-leaf telegraph, depending on the same principle, was introduced by Paton in 1846. These two instruments preceded Einthoven's by many years. In stating this, I do not wish to detract from the great advances made by Einthoven in designing his instrument.

Mr. A. P. Trotter (*communicated*): The capillary electrometer developed by the late Professor G. L. Burch was used by him in 1894 to photograph telephonic currents (*Electrician*, 1896, vol. 37, p. 517). It seems probable that this method might be used to record heart murmurs.

Mr. R. S. Whipple (*in reply, communicated*): I agree with Dr. Lewis that the microphone at present used for the measurement of heart sounds is unsatisfactory. There is undoubtedly an interesting and useful field of research open to the experimenter who obtains a satisfactory microphone for this purpose.

The movements in the electro-cardiogram to which Dr. Russ refers are not improbably due to muscular tremors. It has been found advisable to pack the electrodes into which the hands are placed with cotton-wool soaked in the salt solution. The wool steadies and supports the hands and greatly reduces the muscular contractions. The string galvanometer is undoubtedly sensitive to mechanical vibration, but as a rule the vibrations met with in an ordinary pathological laboratory or hospital are not sufficient to affect the records seriously. No serious advantage would be gained by cutting down the skin resistance—as a whole, better results are given when the skin resistance is high, since the variation in resistance with slight variation in the depth of immersion of the hands in the electrodes is then almost negligible. I am grateful to Dr. Russ for his reference to Professor Gee's work on the resistance of the human body.

I agree with Dr. Ward as to the advisability of enclosing the moving parts of the control board to protect them from dirt. In all the modern instruments this course is adopted. It is impossible to use the electrodes exhibited at the bedside of a patient, and electrodes of various types with varying degrees of success have been used for this purpose. The electrode designed and shown by Dr. Ward should be of considerable service.

It has not been found possible to make the rotary time-marker start automatically, although they usually start well. Dr. Russ will find that with a little practice it will be possible to start the rotor at the second, if not the first, attempt. I have known a rotor run continuously without any attention for 30 hours.

I am interested to learn from Professor Porter of the instruments designed by Cumming and Paton. The references are of interest owing to the controversy there has been as to the priority of invention of the string galvanometer.

I do not know if the capillary electrometer has been used as suggested by Mr. Trotter for recording heart murmur. The use of the instrument had been revived considerably by the late Dr. Keith Lucas.

THE FULLERPHONE, AND ITS APPLICATION TO MILITARY AND CIVIL TELEGRAPHY.

By Major A. C. Fuller, R.E., Associate Member.

(*Paper received* 4 *March, and read before* The Institution 24 *April*, 1919.)

It is well known that if a stretched wire or a reed or certain other forms of elastic bodies such as stretched parchment, metal plates, etc., are caused to vibrate within the limits of audible frequencies, a note—more or less musical—will be produced.

A very simple way of producing such a note is to pass through an ordinary telephone receiver a current interrupted at the required frequency. This leads us to the very simple diagram shown in Fig. 1.

It is obvious that a note at the frequency of the interrupter will be heard in the telephone as long as the key is depressed. Further, it is apparent that audible signals consisting of long and short notes will be heard if the key is manipulated in accordance with the Morse code. Hence the diagram indicated in Fig. 1 is in itself a conceivable telegraph system and can be shown as in Fig. 2. Such a system has many disadvantages, which are at once apparent and need

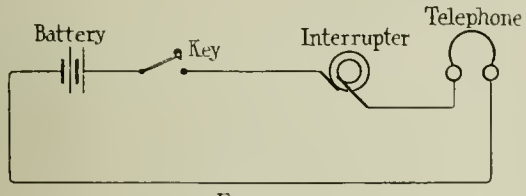


Fig. 1.

not be considered here—but at the same time it has at least one very great advantage, namely, that an exceedingly minute current arriving at B will give an audible signal.

Authorities give various figures for the minimum current capable of producing an audible sound in a telephone receiver, but certainly 0·0000005 ampere is sufficient. The author ventures to say that no other telegraph instrument equally robust will indicate the received signal (wire telegraphy is here referred to) so positively with so small a current. He is well aware that there is considerable prejudice against the use of telephones for receiving telegraphic signals—such, for example, as the alleged tiring of the operator, etc. The Fullerphone, however, in which the signal is similarly read, was primarily intended for military work, and the military operator concerned was already used to such reception, this being standard on the vibrator system which the Fullerphone was destined to supersede.

Such a system as indicated above is not employed in the form shown, and is certainly not so good as the vibrator system. The same vibrator system, however, has certain very serious disadvantages, of which the following were some of the most important.

(*a*) As the name implies, the line was traversed by vibratory currents, and these currents, in order to traverse lines of high resistance, were of relatively high voltage. Such currents, of course, induce similar currents in other lines in their proximity; hence the number of possible lines on one route was strictly limited, owing to the interference—cross talk—or jamming between the various lines. One can easily realize that military considerations frequently require several lines along one route and, even with two lines, care had to be taken to keep them as far apart as possible.

(*b*) Owing again to the vibratory character of the current, the length of lines over which the vibrator can be used is strictly limited by their capacity.

(*c*) By the use of suitable apparatus these vibrating signals can be read at immense distances from the line, and hence any messages can be overheard—the

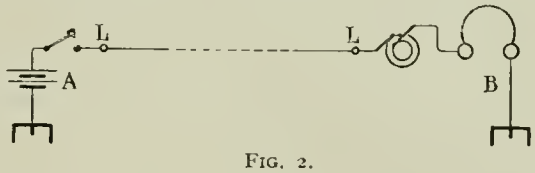


Fig. 2.

author will refer to such apparatus by the general name of listening-sets.

(*d*) The use of vibrators in any area effectually jams in that area friendly listening-sets which might otherwise overhear enemy messages.

(*e*) It is manifestly impossible to superpose the vibrator system on telephone lines.

At this point it may be as well to indicate why, with these serious disadvantages, the vibratory system was ever introduced into the Army. In the first place, the sets are very robust and very portable. They require very little care or adjustment and no skill to manipulate—they work admirably over lines of very high resistance—and it should be borne in mind that military lines in forward areas are necessarily frequently of fine steel wire with as high a resistance as 1,000 ohms per mile. The battery power required is very low and the current output is also low. These sets have in fact served their purpose admirably in former wars and appeared quite suited to military requirements antecedent to this war.

In order to produce something more suitable than the vibratory system, it was necessary to retain as many

of the good points just indicated as possible, at the same time substituting something less troublesome than the vibratory current. Obviously Fig. 2 still provides a vibrating or—more correctly—pulsating current on the line, or at any rate on a portion of it, and is of no great practical value. The solution appeared to be the provision on the line of a direct current as in ordinary single-current Morse, but of as low a value as possible—at the same time converting the energy thus transmitted into vibrating or pulsating current at the distant end—and further, such vibrating or pulsating currents had essentially to be closely confined to the distant end and prevented from surging back along the line.

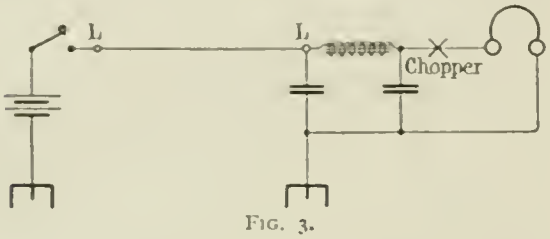


Fig. 3.

Fig. 3 shows the first method used. This was found to be satisfactory, but before proceeding to describe its action let us consider Fig. 4, which provides a better arrangement and is essentially the circuit adopted.

K_1, K_2, K_3 are condensers each of 1 microfarad. CH_1, CH_2 are choke coils of large impedance, each about 2·4 henries and 750 ohms resistance. The chopper is an electrically-driven vibrating interrupter fitted with two contacts, one of which is used to drive it, the other to interrupt. The chopper or buzzer can be adjusted to any frequency between 300 and 600 or 700.

The receiving circuit is shown in Fig. 4. Now, if a steady electromotive force is applied between the line and

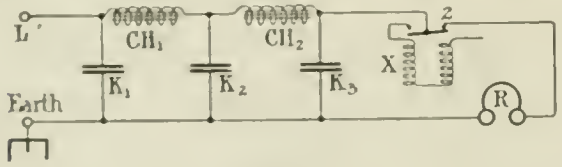


Fig. 4.

earth, and the circuit is closed at X, a steady current will flow through the choke coils, contact 2, and receiver. If the circuit is broken at X, the current cannot flow through the receiver but will flow into and charge the condensers. When the circuit is again closed at X the condensers partially discharge through the receiver R.

When the interrupter X is working we therefore get an intermittent current in the telephone receiver, giving an audible note, while the choke coils and condensers are suitable the line current alternately flows through the receiver and into the condensers, and remains practically constant and continuous in the line. The result is that the dots and dashes sent by the single-current Morse key at the far end are received as short or long notes in the telephone receiver at the receiving end, while the current in the line is of much the same nature as that sent by an ordinary single-current Morse set, except that it is very much smaller, as readable signals can be obtained with about $\frac{1}{2}$ micro-ampere. In practice a main battery of one dry cell is used.

The signals are much clearer than those from the "buzzer," as the commencement and end of a signal do not depend on the starting and stopping of a vibrating armature; hence the rate of working is higher than with a buzzer—always assuming that the operator is sufficiently skilled.

The arrangement of choking coils and condensers not only prevents any appreciable variation in the line current, but also prevents any vibrating currents (such as are produced by induction from other circuits, by a buzzer on the line, or from a telephone) from passing through the operator's head telephones. All such currents pass through the condenser K_1. Should any vibrating current make its way through CH_1 it will then take the path to earth through K_2 rather than through the high inductance CH_2; thus the telephones are doubly protected from induced currents or from telephone currents passing over the same line.

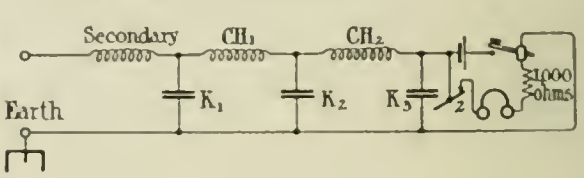


Fig. 5.

When the sending battery is connected as shown in Fig. 5 the current can only rise in the line comparatively slowly, owing to the effect of the capacity of the condensers and the self-induction of the choke coils. The object of this retardation of the rise of current is to prevent clicks being heard in a telephone receiver inserted in the line. This has a twofold object:—

(*a*) To prevent the possibility of Morse messages being read from these clicks.
(*b*) To prevent the clicks interfering with telephony carried on over the line simultaneously with Morse signalling.

It will be noticed that the Fullerphone is not a polarized instrument, and that the direction of the received current does not affect the signals. The arrangement of chokes and condensers acts also in the other direction, thus ensuring that the vibrating currents in the circuit K_3 2 R are confined to this circuit and cannot surge back into the line.

It is apparent that a telephone can be added on the same line without any interference between the Fullerphone and the telephone as far as speech is concerned, and in the latest Army instrument a telephone has been incorporated. Clearly if a separate telephone instrument is used it must be joined up in series with the Fullerphone. Fig. 6 shows how the Fullerphone may be, and is in fact, superposed over telephone pairs

in the usual way. The bridging coils may be of very high resistance and large impedance, and the telephony is therefore quite unaffected.

Fig. 7 shows an alternative and simpler method. The disadvantage of Fig. 7 is that the telegraphic signal in the Fullerphone is jammed when the telephone calls up by magneto generator. The Fullerphone proper has no effect on the telephone.

Calling arrangements with Fullerphone.—For the Army instruments for field use an arrangement has been made to send a strong buzzing current to the line for purposes of calling attention. The interrupter buzzer is used for this purpose and its ordinary battery is reinforced by two additional cells, making three in all. This call is considerably louder than the Fullerphone signals if the line is comparatively short and in

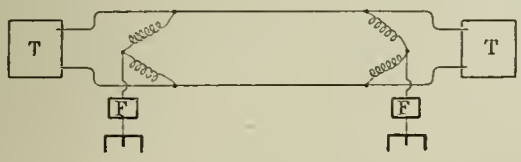


Fig. 6.

reasonable condition, but if the line is of very high resistance or capacity the Fullerphone signals will be louder than the buzzer signals.

The buzzing call can be relied on in normal conditions, but if the circuit is very bad it may be possible to call and send messages on the Fullerphone when the buzzing call will not get through. In such cases it is necessary to call with the Morse key and to " listen in " at short intervals on the Fullerphone to ascertain if the station is being called.

It must be remembered that the buzzing call has all the disadvantages of the buzzer and, consequently, must never be used near the front line for sending any

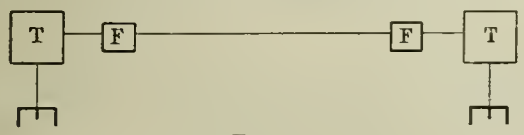


Fig. 7.

call or signal which it is important that the enemy should not overhear.

Disturbance due to earth currents or leakage.—Difficulties in working the Fullerphone are almost invariably due to small currents being picked up by the line either by the earths, by earth faults, or by leakage from Morse circuits. The currents to cause this disturbance must be of a steady nature, or of a very low frequency. High-frequency currents (such as are produced by a buzzer, or telephone speech) or disturbances induced on the line do not affect the working of the Fullerphone. The effect of the steady current is to produce a note in the Fullerphone receiver of exactly the same pitch as the received signals, which are thereby confused and may be rendered unreadable. This disturbance can only be noticed when the local buzzer is running.

Disturbances due to induction will affect the telephone, if such is incorporated in the Fullerphone, in the same way that they will interfere with any other telephone.

Earth currents.—An earth current on the line causes a continuous hum in the Fullerphone receiver when the local interrupter is running. If the earth current is in the opposite direction to the signalling current sent out by the sending station, the signal received when the sending key is depressed will be that due to the difference between the sending and earth currents, while the sound when the key is not depressed will be that due to the earth current only. Hence, if the received earth current is half the received signalling current, the

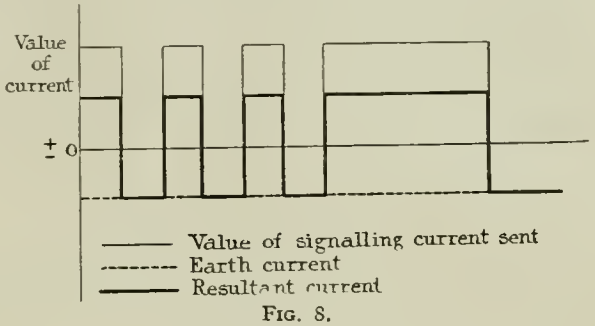


Fig. 8.

current will be altered in direction but not in magnitude when the sending key is depressed, and no signals at all will be received.

If the earth current is greater than half the signalling current the signals will be actually reversed. If the currents are equal there will be silence at the receiving end when the key is depressed at the sending end. If, on the other hand, the currents be in the same direction, the signalling current will always increase the earth current, and the signals will always give a louder note than the earth current alone.

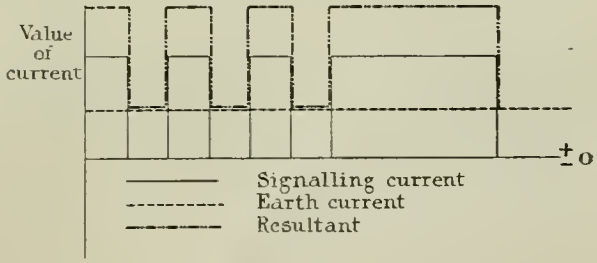


Fig. 9

If the received earth current be half the received signalling current, the result will be an increase in current in the proportion of 1 to 3 when a signal is being sent, which will frequently be readable.

Hence the disturbance due to steady earth currents in a direction opposite to that of the signalling current can always be reduced (in most cases sufficiently to work the line) by reversing line and earth at the sending end, thus bringing both currents in the same direction.

The increase of sound due to an increase in the current through the receiver does not depend merely on the magnitude of the increase or even of the relative

increase, but the weaker the current the greater is the audible effect of a given increase, or even of a given relative increase. Hence, if the earth or leak current gives a loud note the signalling can be improved by increasing the resistance of the circuit, which is most easily done by increasing the resistance of the earth. A good earth is not required for the Fullerphone and may even be a disadvantage.

Use of potentiometer.—The disturbance from a steady earth current either from a leak or from the earths can always be eliminated by the insertion of a potentiometer in the line at the receiving end, and such a potentiometer forms a component part of the service instrument. The potentiometer consists of a length of high-resistance conductor through which flows a current from one cell. One end of this conductor is connected to one terminal of the potentiometer, and a sliding contact (which can be adjusted to make contact with any portion of the conductor) is connected to the other. The potentiometer is connected in series in the line and impresses a portion of the electromotive force of the cell on the line. If the electromotive force thus impressed on the line is equal and opposite to that producing the earth current, the earth current and its disturbances are eliminated.

Each station must adjust its own potentiometer to suit the earth currents received by it. As the currents are frequently picked up at earth faults, they will not necessarily be the same at each end of the line.

Leakage currents from Morse.—Where Fullerphone and Morse are employed in the same telegraph office, or on the same pole route, a leakage current from a single-current Morse set will cause the signal from such set to be heard in the Fullerphone receiver when the interrupter is running. A similar current from a double-current set or duplex will give confused signals. In either case they may be strong enough to interfere with the Fullerphone signals.

If such currents leak on to the Fullerphone circuit at a contact on the line, the only thing is to clear the contact. Such leakage, however, frequently occurs at the office, owing to leakage either at the test board or at the earths.

The same earth should not be used for both Fullerphone and Morse circuits, or interference is almost certain to result. The best earth obtainable should be used for the Morse, and an inferior earth used for the Fullerphone. The earths should be as far apart as possible and the wires leading to them should be kept clear. A bad earth will not be disadvantageous for the Fullerphone proper, unless very bad indeed, but the speaking (if such is required) may suffer. If there are Morse and Fullerphone instruments in the same office the circuits and their earths should be kept entirely separate.

It must be remembered that the Fullerphone is very sensitive and one 1,000th part of the current usually employed in Morse working will give strong signals in the Fullerphone.

Explanation of circuits.—Fig. 10 shows the circuits

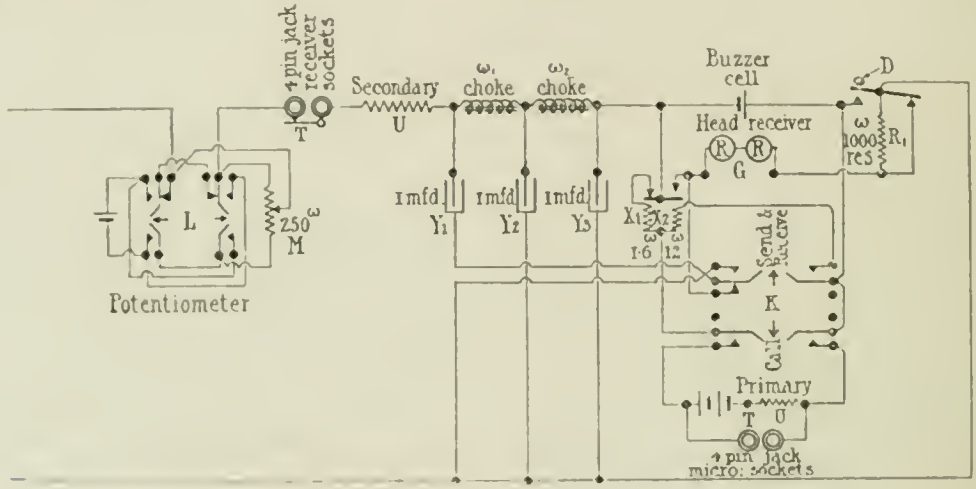


FIG. 10.

of the latest pattern Army field set. This instrument provides for telegraphy and telephony either independently or simultaneously on the one line without further apparatus. When the receiving buzzer is not working, the buzzing call from a distant station is heard both in the head receivers and in the hand set—or if the hand set is not plugged in, only in the head receivers.

When "Fullerphoning," the Morse signals are heard in the head receivers only.

When speaking and telegraphing, the speech is heard in the hand set and the Morse signals in the head receivers.

In order to show clearly the operation of the various circuits Fig. 10 is dissected into Fig. 10 (A), (B), (C), etc. It should be noted that when the 4-pin plug is inserted the line is completed through the receiver of the hand set. When the plug is withdrawn the receiver sockets are short-circuited by a spring contact.

We have so far considered the instrument almost entirely from the military point of view, and before proceeding to uses in a wider field it may be as well to consider certain tests, etc. The first essential was

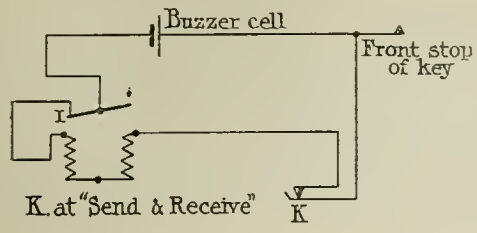


FIG. 10 (A).—Local chopper circuit.

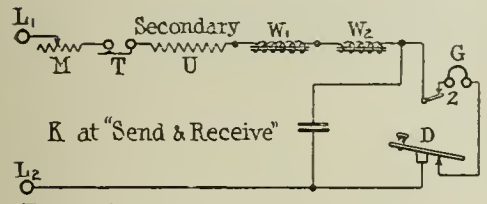
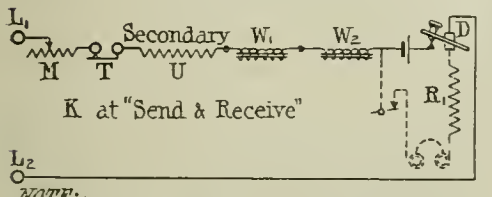


FIG. 10 (B).—Fullerphone reception of Morse.



NOTE:-
Dotted line shunt circuit to allow the operator to hear his own outgoing signal & to test his own buzzer

FIG. 10 (C).—Sending Morse.

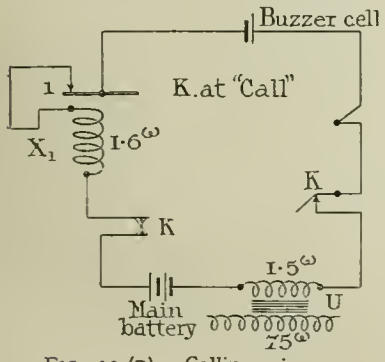


FIG. 10 (D).—Calling primary.

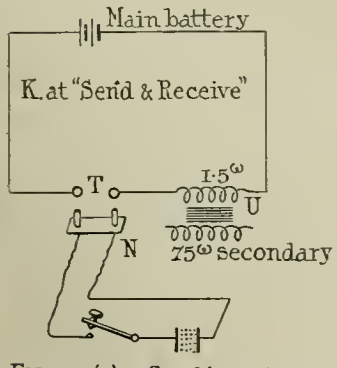


FIG. 10 (E).—Speaking primary.

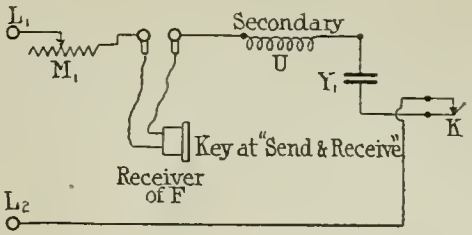


FIG. 10 (F).—Secondary speaking (while Fullerphoning).

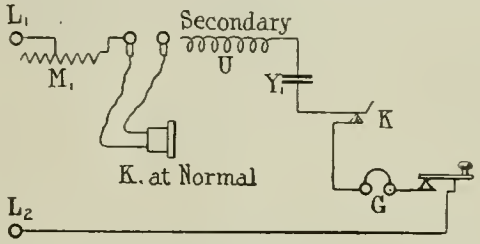


FIG. 10 (G).—Secondary speaking (while not sending) and secondary calling.

that the system should be non-inductive. The fact that no sound is heard in a telephone receiver inserted in the line is itself practically conclusive.

Fig. 11, which is a reproduction of oscillograms kindly made by the Research Department of the G.P.O., affords further proof.

The gradual and slow rise of current shown in Fig. 11 (A), and referred to earlier, accounts for the fact that not even clicks are heard in the line.

Exhaustive tests have been made to ascertain whether the system—using a single wire and earth return—is safe from the possibility of being overheard by enemy listening-sets. It was found that under ideal conditions for the listening-set, and using the best listening-set that we could devise for the special purpose, the messages were safe from overhearing at a distance of 100 yards from the line. It should be noted also that these ideal conditions would never obtain in practice in the field.

The following laboratory test was made to determine the minimum current required to operate for legible signals. The above values gave readable signals where I the current passing through the instrument, was approximately

$$\frac{3}{8{,}000} \times \frac{1}{800} \text{ ampere} = \frac{3}{6{,}400{,}000}$$

or less than $\frac{1}{2}$ micro-ampere.

The above indicates that the system will work over lines of immense conductivity resistance and very poor insulation. In practice we have often worked earthy lines of which the conductivity resistance was far greater than the total insulation resistance. On another occasion a trial was made in wet weather of a line consisting of bare copper wire lying on the ground and an earth return. The line was workable, but with difficulty.

Before the system was adopted for the Army the author had the privilege of testing it over some specially selected lines in Flanders in 1915. The lines were

selected chiefly on account of their unpleasant location and necessarily bad condition, where the ground was waterlogged and pitted with shell holes, and maintenance was anything but easy. Some results of tests made by the Research Department of the G.P.O. on early instruments made by them are appended. The author is confident that the later sets would give even better results.

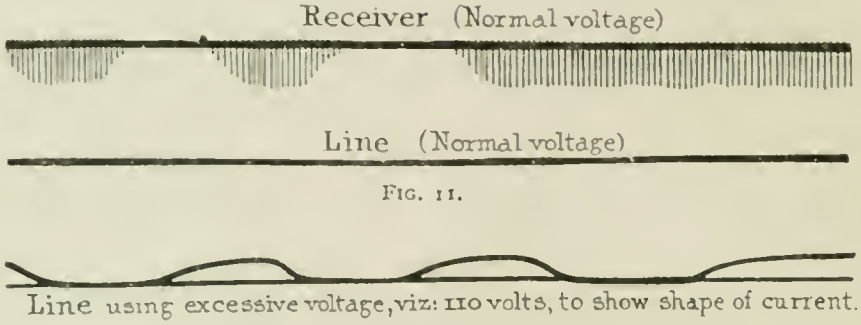


FIG. 11.

FIG. 11 (A).

The limiting working lengths were obtained for the following four conditions :—

(1) Test circuit of "standard cable" twin copper conductors, 20 lb. per mile, paper insulated.

Result : Well over 155 miles (no further "standard cable" was available).

(2) Circuit having high resistance factor, consisting of variable resistance R joined between two 10-mile lengths of standard cable.

Result R—approximately 200,000 ohms.

(3) Circuit having high leakance factor ; variable shunt R in centre of 20 miles of standard cable.

Result R—6 ohms.

(4) Circuit having high capacity factor ; variable capacity K in centre of 20 miles of standard cable.

Result K—over 90 mfd. (No greater capacity was available—trials were, however, made on Messrs. Siemens' artificial submarine cable, when signals were perfectly good through 370 miles, the longest cable available, with a capacity of 135 mfd.)

These figures speak for themselves and it seems that, provided the line is not actually broken, it can be worked by Fullerphone almost irrespective of its general conditions.

Application of Fullerphone to civil telegraphy.—From experiments and trials recently made it has been established that the Fullerphone can replace Morse sounder sets on any hand-worked line. The advantages to be expected include the following :—

(*a*) Great saving of battery power.
(*b*) Simplicity of office wiring and manipulation of instruments.
(*c*) Very long distances can be covered without translation or relaying.
(*d*) Maintenance of lines can be reduced to a minimum.
(*e*) Lines may be of very high resistance—strength would probably become the ruling factor rather than conductivity.
(*f*) Lines may be very leaky and contacts with foliage, etc., are of slight importance.
(*g*) No disturbance whatever is caused to neighbouring or parallel telephone circuits, and no disturbance need be feared to telephone circuits when Fullerphone is superposed.
(*h*) It will be possible to work long stretches of land line and then cable and land line again without any conversion or re-transmission. These possibilities have not yet been tested to the limit.

In order to be applicable to civilian uses the instrument is altered from that already described. In the

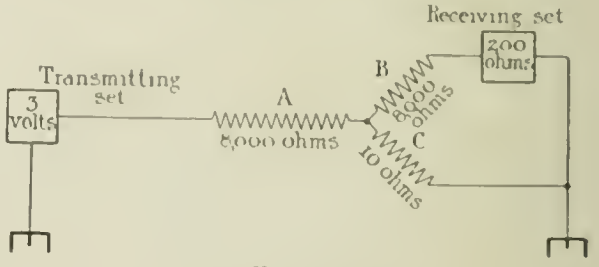


FIG. 12.

first place, the buzzer call is objectionable and is discarded. It has two serious disadvantages for other than military work :—

(1) The call does to some extent interfere with superposed telephony.
(2) The buzzing call transmitted is not loud enough to attract attention if the office is noisy or the operator not at his instrument. Further, capacity strictly limits the length of line over which the buzzing call will work, and the call would fail long before the signal proper.

A method of direct current calling has therefore been devised and this is satisfactory.

Fig. 13 shows the circuits for other than field use in forward areas.

The following points should be noted :—

The main relay which receives the direct current call is protected (by the chokes and condensers) from telephonic, vibrating or induced currents.

This relay is an enclosed moving-coil instrument and is very sensitive. It is provided with a shunt (variable) so that its sensibility can easily be controlled.

A further addition to be noted is the two-way switch marked " Internal " and " External."

The object of this is to enable the chopping for any number of sets to be done by one multiple chopper independent of the sets. Where several sets are working in one office the combined noise of all their choppers might be rather trying to the nerves, and would at any rate destroy the quietness which should be aimed at in a telegraph office.

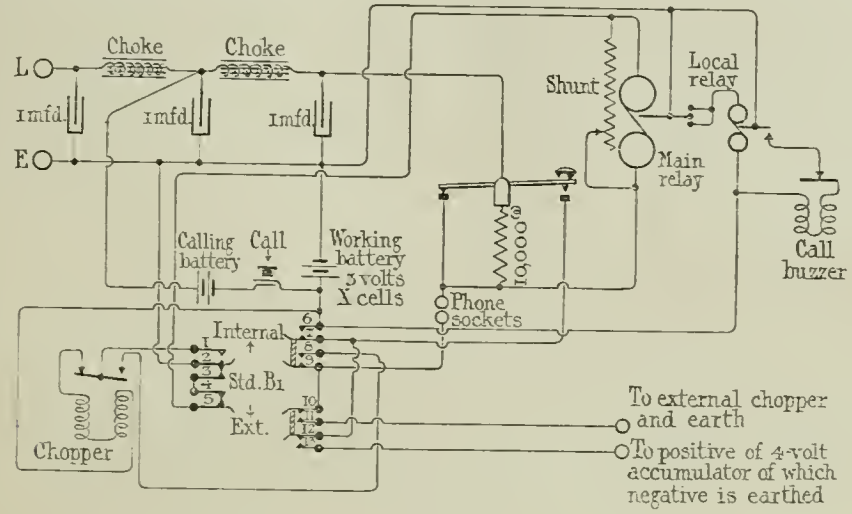


Fig. 13.

The relay is a slow action one and is therefore very suited for responding to a calling dash, but is not suited for telegraphy as an ordinary A or B relay.

The second or local relay is very small and is used in order to handle the current actuating the calling buzzer (or bell). This current would be prejudicial to the prolonged satisfactory working of the main relay.

A call is sent out by pressing the push-button shown. This puts a small 3-cell " Ever-ready " battery in series with the working battery, thus sending a current of short duration from a battery of about 7 volts to operate the distant relay.

The act of calling also tests the home apparatus for receiving a call. The local calling buzzer should operate when the push-button is pressed.

This arrangement will work well through very long and very bad lines.

When attention has been obtained the work is carried out by Fullerphone proper, for which the 2X cells alone are employed.

It should be noted that the main relay is capable of reliable action with a current of the order of 10 micro-amperes.

As 6 or 7 volts are available when the call-button is pressed, the relay will respond through a resistance R, where

$$\frac{1}{100{,}000} = \frac{7}{R}; \quad \therefore \ R = 700{,}000 \text{ ohms.}$$

This assumes, of course, that the shunt across the relay is disconnected.

By the arrangement shown, however, the chopping for all sets can be done outside the instrument room by a multiple buzzer—which runs almost indefinitely without attention. The author constructed multiple choppers to deal with 6 and 10 circuits each, which are driven by a 4-volt accumulator and only require a very small current—about 150 milliamperes.

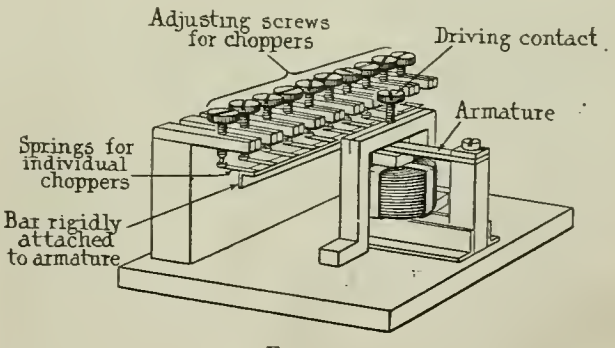


Fig. 14.

Using such a system, one small 4-volt accumulator is sufficient to work the whole office. It drives the buzzer and so effects the chopping, and it also provides the minute signalling currents for all the lines.

The internal position is provided so that any set is entirely self-contained and forms an easily portable and readily connected unit (power included) for small offices.

Duplex.—Fig. 15 shows the instrument arranged for

duplex working. It will be seen that the bridge method is employed. This method is very suitable and the usual objection to bridge duplex—namely, the increased battery power required—does not hold, owing to the extreme sensibility of the receiving system.

Exchange working.—A further point to be borne in mind is that the system is admirably suited for exchange working. It makes little difference to the signal whether the line over which it is transmitted is 100 miles, say, longer or shorter; hence the present necessity for re-transmission at intermediate stations is removed and direct through plugging can be employed.

Recording or printing.—By the use of auxiliary apparatus the system can be used quite satisfactorily where recording work at relatively high speeds is required. By means of a relay of special design invented by Captain L. B. Turner, R.E., and modified for high-speed work, the aural signal received can be readily made to operate an ordinary telegraph relay at high speed, hence direct-printing systems such as the Creed can be employed.

In the same way the signals received can, after amplification, be uprighted and made to give beautiful records on a siphon or other recording device.

Cables.—The author has not yet had an opportunity of ascertaining to what extent the system can be advantageously applied to cable practice, but with our present knowledge of amplifiers and the possibilities opened up by experience with the 3-electrode valve, great advances in submarine telegraphy are assured. The normal audible signal produced by the method is already of such a character that it is admirably suited for operating on the grid of an amplifying valve. The telephones are, for this purpose, replaced by the primary winding of a suitable transformer, the secondary winding being connected to the grid-filament of the valve.

Conclusion.—To sum up, the present position is that for military work the Fullerphone has practically superseded the vibrating system formerly employed. It is now being tried for working long lines in back areas, where it will almost certainly replace all hand-worked Morse sounder sets. It appears, therefore, that, as far as line telegraphy is considered, the Fullerphone system will be used throughout, except—for the present, at any rate—for those lines normally working high-speed Wheatstone. These Fullerphones will be of two patterns—the trench Fullerphone—which is weatherproof and well protected—for the forward area, and the office pattern further in the rear. For civilian use, one cannot expect sounder sets that are established and giving satisfaction over well-constructed routes to be discarded in favour of Fullerphones; but it is expected that the advantages to be derived from the new system will lead to its adoption in countries not already thoroughly developed from a telegraphic standpoint.

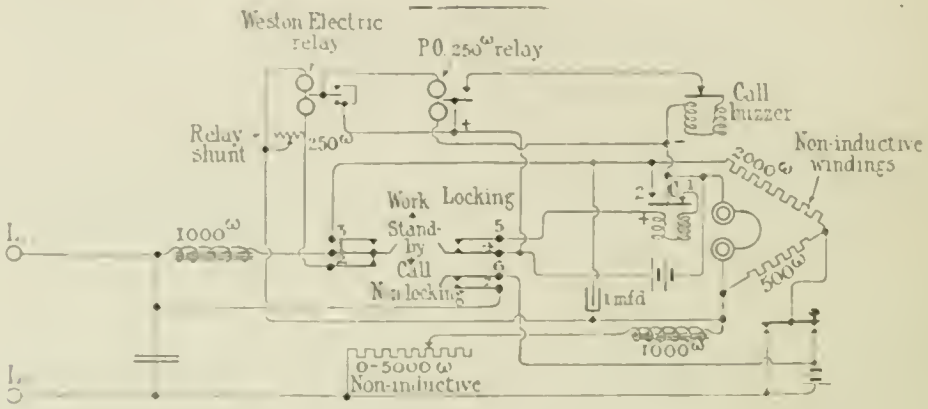


FIG. 15.

An opening should also arise in tropical countries where maintenance difficulties are considerable—and it is probably not too much to say that the system described would give satisfaction wherever difficulties from any cause render Morse sounder working precarious. For cable work the author feels—with due deference to certain experienced submarine telegraph engineers—that an investigation of the possibilities of a system combining Fullerphone, amplifiers, special existing relays, and recording and printing devices, would prove very profitable.

The development of such a scheme as he has in mind would take a paper to itself and cannot be further considered here. Before closing he feels that he must take this opportunity of acknowledging with gratitude the help which he has received at various times from several brother officers—notably, Lieut.-Colonel Evans, C.M.G., D.S.O., R.E., Major E. O. Henrici, R.E., Major Purves and others whose suggestions have proved very valuable.

Discussion before The Institution, 24 April, 1919.

Mr. W. Judd: I remember reading some 30 or 40 years ago of a device by, I think, Van Rysselberghe, an official of the Netherlands Telegraph Department, which practically makes use of the principle introduced by the author, that is, of slowing the rate of rise and fall of the Morse signal by the application of inductance or by some other retarding method. It was not many years after the telephone was first introduced. Van Rysselberghe superimposed a telephone circuit on an ordinary Morse line without disturbing the telephone, but he had to abandon the method because the slowing down of the rise and fall reduced the speed of working on the Morse line to such an extent that the administration could not continue it. The author has, therefore, made use of a known principle, and improved and perfected it. The second thing which I think has been made use of admirably by the author, is the splitting up of these more or less distorted signals arriving at the further end, so that they should become audible in the telephone. That has been done before by Heurtley, and I think by Brown, and certainly by some of the cable companies. It may be of interest to say that when raiders showed some inclination to smash up cable stations and destroy all the apparatus, it was thought wise to see whether some emergency device could not be developed whereby communication might be made with stations treated in that way. We sent out instructions that stations should connect a telephone, big choke coil, or magnetic shunt of low resistance and considerable inductance, a vibrator of the simple form used for vibrating the siphon of the recorder, with the necessary key and battery, to be buried somewhere or other, so that in case of trouble they could be dug up and some sort of communication established, if the end of the cable was accessible under circumstances such as I have described. This worked very well. But obviously it had to work on Morse signals. Double-current Morse is no good, because the telephone responds to the spacing current as well as to the marking current. Equally certain, on a long cable single-current Morse is no good, because unless one sends at a very low speed the separate dots will not come out at the other end. As a matter of fact, on a cable 2,000 or 3,000 miles long, one dot comes out as a little hump, and two dots in succession come out as a little longer hump, and if we send 50 dots they come out as a long hump; there is no division into dots at all. We then decided that we would adopt the inverse-current method of Delaney. In the letter S, for instance, starting the first dot negative, the second positive, the third negative, or the first one may be positive, dependent on what has gone before; so that we get three dots, each one on the opposite side of the zero line. We chopped these signals up as they came along with the vibrator, and in cables up to 3,000 miles we were able comfortably to receive at a rate of 12 to 15 words a minute, so that the chopping up was quite efficient in that way. I will leave the land-line question to those who have had more experience of it, but for the purpose of working cables on this method we have, as far as I can see, to send our signals into the cable on the inverse-current method. I do not know what valves will do for us, whether they would be so excessively sensitive and so very perfect that they would show the dots coming in rapid succession. The disturbance on land-line circuits, I imagine, would be practically eliminated by the Van Rysselberghe method in the same way as with the Fullerphone, but the Fullerphone itself has undoubtedly brought both these methods, that is to say slowing down the rise and fall of the current and splitting up the received current to render it audible, to a perfection that reflects the very greatest credit on those who worked it out so well.

Lieut.-Colonel Ll. Evans: There is only one point I should like to emphasize, and the author referred to it, namely, the difficulties that occurred on the first introduction of the Fullerphone. The Fullerphone was introduced in a hurry, and sufficient previous instruction in its use could not be given. The result was a considerable amount of prejudice, which is gradually being overcome, although I believe there is still a good deal left in the Army against the instrument. I attribute that to the lack of instruction in the first instance, to certain defects which occurred in the earlier pattern of instrument, and to the fact that numerous patterns of instrument were produced, with the result that at the two ends of a line one might have different types of instrument which the operators could not explain to each other. One other difficulty which was met with originally, and which for lack of time for instruction we failed to elucidate to the users, was the disturbance from earth currents or leakage currents. The potentiometer was introduced to overcome that, and the instrument re-designed, but, again due to lack of instruction, great difficulties occurred which would have been avoided had there been longer time in which to instruct the operator and the officer. I emphasize these points because though I believe there is still some prejudice against the instrument, it is the intention that the instrument should be very widely adopted in the Army, although it is not quite possible to say that we can at present discard the sounder or the buzzer.

Mr. H. H. Harrison: The particular principles of the apparatus which has been described to us to-night are to be found in two early specifications of the French telegraph engineer, Clement Ader, Nos. 7625 and 17528 of 1887. Those specifications are interesting because they show not only methods of employing land-line Morse, but also methods by which cable Morse can be utilized. The principle disclosed is generally on the same lines as the Fullerphone, namely, weak direct-current signals to the line chopped up by a rotary commutator at the receiving end. That being so, one is compelled to look closely into the matter to see what other steps exist in the arrangement that the

author has described. I think they may be said to be two in number. First, there is the filtering arrangement, consisting of a combination of inductance and capacity by which inductive troubles from vibratory currents in the neighbourhood are excluded from the telephone, and secondly the arrangement by which a receiving condenser is charged over a comparatively long time and discharged in a very small space of time, thus giving an apparent amplification of signals. I cannot share the author's sanguine views with regard to the universal employment of the Fullerphone in civil telegraphy. First of all, as I understand, it is a hand-worked instrument. It is true that we can work it on quite long lines, but it would not be economical or efficient to work such an instrument on an expensive long line, because a speed of 30 or 40 words a minute in a line running into £40,000 or more cannot compare with an automatic or machine telegraph. Then again, as I see it, there will be difficulty in obtaining a satisfactory duplex balance. The instrument is exceedingly sensitive, the working current being of the order of 1 1,000th of that of the ordinary telegraph apparatus. Anybody who has had any experience of duplexing difficult land-line circuits with the existing apparatus will know that those difficulties will be intensified with such an instrument as the Fullerphone. One could employ it on a loop, and if the wires were on the same poles and were similar in their character-

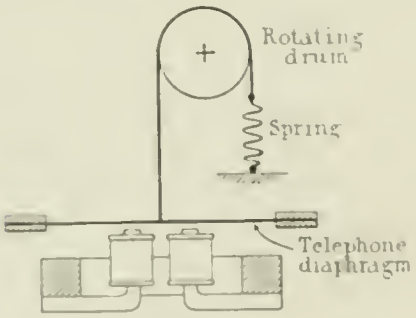


FIG. A

istics some of the difficulties would disappear. Another difficulty I see in the universal employment of the Fullerphone is that it would be subject to disturbances from high-speed circuits, tramcars starting and stopping, electric railways, etc., all of which would hopelessly jam the apparatus. The author has referred to the disadvantage of using the buzzer as a calling device in any such instrument. My company has also given some attention to this matter, and I have brought with me for exhibition to the members a specially designed relay of the integrating type, the construction of which is diagrammatically indicated in Fig. A. The problem was to be able to close a local circuit and ring a bell from buzzer signals. A small phosphor bronze wire passes from the middle of the diaphragm round a horizontal arm and is anchored by a flat leaf spring. Buzzer signals rotate the drum. With a note of frequency of about middle C the drum will rotate about three or four times per second. At the end of the drum an arm is carried gradually round by friction, and ultimately closes a contact, ringing a bell. The apparatus works so rapidly that one can even use buzzer Morse signals to control a Morse sounder. Kinematically the apparatus may be classified as a silent or friction ratchet. Each downward excursion of the diaphragm tightens the cord and rotates the drum through a small angle. The inertia of the drum prevents backward motion when the tension is relieved. The rotation of the drum is an integration of a large number of tiny steps and hence the device may be called an integrating relay. Before it is possible to accept the author's conclusions, we require to know more as to the behaviour of the Fullerphone on duplex circuits and its susceptibility to disturbance, not from vibrating currents, but from Morse currents on the same or adjacent pole routes.

Mr. A. C. Brown: While congratulating the author on the way in which he has worked out the Fullerphone, I have the rather thankless task of claiming to some extent a prior invention. In 1896 I invented, as I thought, a complete set of apparatus almost exactly as shown to-night, and I worked it out and made many sets and patented it. How I got my patent I do not know, after what we have heard about Van Rysselberghe's arrangement, if that arrangement was really an anticipation. I had then a means of sending out direct current from the sending end, and of splitting up that current at the receiving end of either a continuous or broken line. The apparatus was made principally to work through broken wires or cables, splitting up the current by means of a silent contact on a locally-driven vibrator, and then putting it through a telephone to earth. Sets of apparatus were used in fact for working through broken submarine cables by the Direct United States Cable Company, and did keep up communication through broken telegraph cables for a considerable time; and they were also used by the Europe & Azores Company, and I believe some were used by the Eastern Telegraph Company. I will put on the screen a slide of my apparatus. That diagram is taken from the patent specification. On the left is the battery and sending key, sending a direct current out to the line, and that current is received at the receiving end through a telephone having in series with it a silent contact, that is a contact not having any other current passing through it except the line current, which contact is vibrated rapidly by a local buzzer. At first sight it appears to have no wave straightener, but it has a very effective one. It is principally designed to be used, and was used, on submarine cables. The cable itself is a complete wave straightener, that is to say it is a combination of the inductance and capacity, the capacity being even more than is wanted. If more is required, more can be added, but the cable has more capacity and quite as much inductance as is necessary. Those accustomed to submarine telegraphy will know that the artificial cables used to balance the real cable for duplex working are made up of alternate resistances, which also have a little self-inductance, and shunt condensers. Since those artificial cables balance the real cable it follows that the real cable itself has enough reluctance and capacity to operate as a

wave straightener, and, in fact, did so work. The second figure shows my arrangement for preventing earth currents. The author has described a good method of curing earth currents, but I went on the lines of preventing them. Instead of a direct-current key I used a reversing key, with the important addition of a small condenser in series in the circuit at the receiving end, and that condenser simply shuts out earth currents altogether, after first joining up the instrument. If an earth current varies very greatly it will finally upset that arrangement, but by the time it does that I guarantee that it will upset any other apparatus that can be used. The reversing current sends a little charge in or out, which passes through the telephone. It is true that this slightly lengthens the period of signal as against the period of break, but so also does the author's and everybody else's condensers which are in shunt with the conductors. They put a little longer current through the telephone during the spacing period. I think that my arrangement will be found to prevent earth currents as well as anything that has been shown up to the present, certainly anything that requires manual adjustment. This apparatus was at the time offered to the War Office, in 1897—the patent is No. 30123 of 1896—but it was not wanted then because it was too early. I have also worked out an arrangement for operating a Morse printer from the telephone signals. We can work a Morse printer with any currents that can be heard to any appreciable extent in the telephone. With regard to sensitivity, I quite agree with the author that the Fullerphone—I am inclined to call it the Brownphone—is certainly very sensitive and does pick up messages which it certainly ought not to pick up. Under those circumstances, and especially with the combination of the thermionic valve, we can pick up everything, and wireless engineers will have to remember that it is not only their antennæ to which they must pay attention, but the whole of their equipment, dynamos, cables, and everything else inducing or producing in the earth currents which can be picked up with these most sensitive instruments. If any young engineers are going on with these experiments, I commend to them to directionize these currents which can be sent through the earth, and if they can it will completely prevent any attempt at licencing. There are a number of other kinds of instruments which of course do the same thing. There is the photophone, which practically produces the same result for short distances, and the thermophone, both of which Professor Bell worked out, and with the former of which I had the honour of helping him. If anyone can only directionize some of these appliances so as to give us a radiophone exchange, it will be a thing which is very much wanted.

Major E. O. Henrici: There have been several remarks to-night about earlier work of the same nature. I have looked up the old records dealing with the early use of the telephone receiver in the army for receiving telegraphic signals, and I find that as early as May 1878 there is a note suggesting that the telephone might be used as a sounder, to receive signals sent by the ordinary Morse key, when the line circuit was too bad for the ordinary sounder to work. They were actually so used in the South African War of 1879–1880. I find also a most interesting report, dated April 1881, signed by Lieutenant Philip Cardew, R.E., who was then instructor in telegraphy at the School of Military Engineering at Chatham. (This report is reprinted below on page 40.) The circuit shown in Fig. 2 of this report embodies the idea of interrupting a steady current so as to make it suitable for reception in a telephone. Fig. 3 is essentially the Cardew vibrator, which is the vibrator system the author refers to, and which has been used ever since in our army and in most other armies. It has proved of great value for military purposes as it will work through lines of high resistance and low insulation. The disadvantages are well known and are referred to by Major Fuller. They were accentuated during the present war by the large number of lines concentrated in small areas, by the proximity of the enemy in trench warfare, and by the development of valve amplifiers. The method of adding choke coils and condensers to modify ordinary Morse signals in the line, so that they should not interfere with telephones or vibrators, is also old. Van Rysselberghe's system is described in "Instruction in Army Telegraphy and Telephony," vol. 1, chap. xvi. Another system using the service store known as the "separator" for superimposing vibrator on Morse is described in chap. xv. This latter system also appears to be due to Cardew, and is described by him in its present form in a report dated 1887. The idea of using a locally-driven interrupter for "chopping" a direct current is also old, but I do not know who introduced it. It might appear from the above remarks that there is nothing new in the Fullerphone, but the fact remains that Major Fuller's combination of these devices, which enables a direct current in the line to be interrupted at the receiving end, so as to actuate a telephone receiver, while allowing no detectable ripple to appear in the line current, is new. If such a combination has been suggested previously, it was not known to the authorities of any of the powers engaged in the war, and was not used in any army until Major Fuller suggested it; it was immediately copied by the other powers, including Germany. To my mind the essential feature of the Fullerphone (the name was *not* proposed by Major Fuller) is the transformation of the received current, without altering the line current. It is in effect equivalent to a rotary transformer, transforming direct current into alternating current. Incidentally the sharp corners of the line current at the beginning and end of each signal are rounded off, and this effect is of advantage on land lines, and has been deliberately increased by introducing the choke coils and condensers at the sending end as well as at the receiving end. The freedom from overhearing or from causing disturbances on other lines is very largely due to the very small currents and voltages employed as compared with ordinary Morse working, or even with vibrator working, the slowing of the rise and fall of the current gives additional protection from overhearing without any corresponding disadvantages in the case of military land lines, for use on which the particular pattern of instrument described was designed.

"*Instructed to experiment with 15 miles of bare wire laid on the ground with a view to ascertain the practicability of signalling through it by means of telephones.*"

"TELEGRAPH SCHOOL,
SCHOOL OF MILITARY ENGINEERING,
"*April*, 1881.

"The wire consisted of 10 miles of No. 16 B.W.G. soft iron galvanized wire, and 5 miles of No. 16 B.W.G. copper wire. This arrangement possessed the disadvantage of keeping a continuous current on the line from the earth contact of the two wires, and of tending to destroy the iron wire, but as the line was only required for a short time, this was not material.

"Permission was obtained from the authorities of the London, Chatham and Dover Railway to lay the wire at the side of their line of rails. It was consequently laid in a loop extending from a short distance on the up side of the New Brompton Station to within a short distance of Newington Station, and back again on the other side of the line.

"To ensure the wire being well out of the way of the traffic, it was laid in the *hedges* in many places. In other places it was laid on the ground, even picketed down under stiles so as to prevent its tripping people

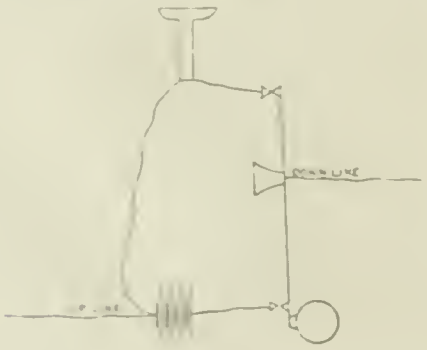


FIG. 1.

up. The ground was generally newly made or garden ground, and the soil of fair conductivity. Rather more than half the wire was thus laid in the hedges.

"At road crossings the wire was stretched over a pole at each side.

"For convenience one end of the wire was brought into the R.E. Institute.

"This necessitated using poles to avoid interference with traffic, and for convenience some poles carrying existing lines were made use of. This introduced induction signals, so that in getting signals through, the following difficulties had to be contended with, viz.:—

"1. Very bad insulation.

"2. Continuous current from the different metals in the iron wire and earths employed.

"3. Induction currents confusing signals.

"The line resistance was never accurately obtained, this being impossible under the conditions, but it must have been about one ohm, while the insulation test from the Institute gave on several days a resistance as low as 300 ohms, which of course included part of the line resistance, the position of the resultant fault being at any rate some distance beyond the end of the insulated wire, so that the true insulation resistance must have been extremely low.

"The first intention was to use the telephones as Morse instruments, with an ordinary key as before proposed, the connection being as shown in Fig. 1.

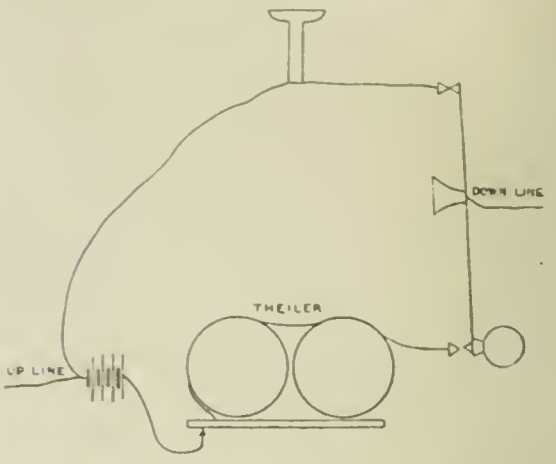


FIG. 2.

"This was tried with batteries of 10 Leclanché cells at each end. At the Institute, in a quiet room there was no difficulty in reading these signals, but the ear had to be kept quite close to the instrument. At the other end there was some difficulty in reading signals when first tried, owing to a very high wind producing noises in the telephone. To get over this I tried the

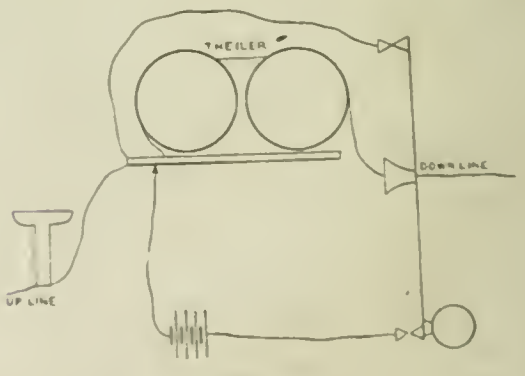


FIG. 3.

effect of putting on a Theiler sounder as in Fig. 2, thus sending a vibratory current out to line.

"This was completely successful, the note produced being very easily read and quite distinct from the induction signals, and the noises due to earth currents.

"Signalling was carried on for several days by this method without any difficulty, clearly demonstrating that by this means signalling can be kept up through bare wire laid on the ground (as rapidly as cable), and afterwards poled and insulated when circumstances permit.

"Another advantage of this use of the telephone is that no adjustment of the receiving instrument is ever necessary, thus eliminating a fruitful source of delay.

"For ordinary insulated lines, the battery power required is very small, and the telephones are ready when necessary to be used in the ordinary way, and would no doubt be found very useful by the General and his Staff as a means of personally communicating orders.

"Another method of connecting the Theiler sounder is shown on Fig. 3. This I think preferable to Fig. 2 in general for the following reasons:—

"1. The current through the Theiler sounder is practically uninfluenced by any change occurring in the line resistance.

"2. In the case of a dirty back contact in the key (a fault of frequent occurrence causing much delay), continuity will still be established through the coils of the Theiler sounder.

"3. Fewer cells can be employed (four cells Leclanché being quite sufficient for ordinary circuits).

"The note given by the Theiler sounder in the telephone is quite as loud as the tone of the ordinary sounder under ordinary circumstances. When working through bare wire laid on the ground it is of course low, but still quite distinct if held close to the ear.

"A simple apparatus for holding the telephone in the required position so as to leave the arms free could be easily designed. Two telephones, one to each ear, might then be advantageously employed.

"From the results of this experiment with bare wire, I feel confident in recommending the employment of this combination of Theiler sounder and telephone in place of the ordinary sounder for field service, over which it possesses the following advantages:—

"1. The possibility, as demonstrated, of working through a considerable length of bare wire.

"2. The receiving instrument requiring no adjustment for altered conditions of line and different stations, etc.

"3. The reduction of the battery power required to be carried to at most one-fourth of the present requirements.

"4. The continuity of the line being ensured, independently of the back contact of the key.

"5. The power of working through very bad earths, saving much time in very dry places.

"6. That the note signals are more easily read than the interval signals by men untrained to either.

"Should this method be adopted, it will involve, to obtain its full benefits, that a certain number of the C Troop Batteries should be altered from 10-cell batteries to 5-cell batteries, the boxes being much lightened.

"The present field service sounders can be easily converted into Theiler sounders, and might possibly, I think, be advantageously fixed on to the lids of the 5-cell batteries which would act as sounding boards to them. The connections with the battery being always complete, so that at any time the battery can be tested by depressing the key, but this has not yet been tried.

"In order to give this method a fair working trial, it should, I think, be tried at Aldershot, and I should suggest that I may be ordered there for a few days in order to fully explain the working of the system to the Officer Commanding C Troop.

"(Signed) P. Cardew, Lieut., R.E.,
"A.I.T.

"P.S.—As regards working with recorders—this of course necessitates the employment of the usual amount of battery power—indeed more cells than usual are necessary to give distinct working signals with the vibrating current. The ordinary working can, however, be resorted to by breaking the Theiler circuit, either at the bridge of the key, or at the armature.—P. C."

Mr. G. H. Nash: The author has referred to the difficulties which confronted the Army when it was discovered that the Germans, having got in the field first with their amplifiers, succeeded most effectively in overhearing all the circuits which were being carried on behind our front-line trenches. The amplifier was more or less a new invention, and it was most unfortunate that the Germans happened to have seized upon its effectiveness and introduced it as a field listening-post before us. The situation to which the author has referred was roughly this. The extremely large number of telephones and telegraph sets in use by our Army at the Front (which go to make up a signalling system of a modern army) were suddenly found to be dangerous to use because enemy amplifier listening-posts were picking up through earth conduction everything carried over the lines of our signalling system located anywhere near our front-line trenches. With telephone messages the distance was two or three miles, but with telegraph sets it was probably greater. It was a most serious condition. I learnt of the trouble through an officer home on leave and, hoping to find an immediate, if temporary, solution, commenced a series of experiments together with a member of this Institution, Mr. R. A. Mack. During those experiments we found that it was possible to jam the enemy listening-posts by introducing interfering alternating currents at various frequencies into the earth at some point in advance of the circuits which were to be protected. It was not in any way an ideal cure for the trouble, but it was a solution which could be temporarily applied to the then existing condition. More effectually to cure that condition required considerable time, for the Army had not only to "metallic circuit" all their lines but to introduce other forms of apparatus which could not be so readily overheard. For a short time at least the various circuits both telegraph and telephone which the Army had out there were temporarily protected from the German listening-posts by the introduction into the earth of these interfering currents called buzzer screens. At first these buzzer screening sets were placed more or less against the front-line trenches, and there produced a jumble of interfering frequencies, which by being picked up by the enemy listening-posts rendered them entirely *hors de combat*. A little later these varying-frequency screening sets were changed to single-frequency sets associated with each line to be protected, and for some little time these carried on, in order to gain time to allow the Army to

[illegible] the lines and to introduce better apparatus. I have been listening to-night to some very pointed criticisms—criticisms which one expects to receive at a technical institution—but I could not help feeling rather sorry for the author in the face of these. The condition at the Front was dreadful. I suppose thousands of men have been killed because of overheard circuits by the Germans, and the author has, I consider, saved a large number of lives by doing something in the years 1916-17 which settled the question of overhearing messages at the Front. Whether his patents or details are new or old matters little; the fact is that he did do it at that critical time, and we all owe him our thanks for it. If the principle of the circuits was known before, I can only say it was a pity that people who had that information did not bring it forward in 1914.

Mr. B Davies: The essential feature of the scheme brought forward in this paper is evidently the conversion

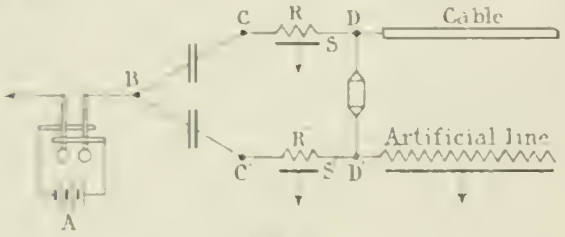


Fig. B.

of a sharp, crisp signal at the sending end into a smooth signal to be transmitted along the line in order to render that line more or less silent. In order to do that the author has reduced the time-rate of change of the current constituting the signal on which the effect depended. I believe this is the first occasion on which a device has been applied at both ends of the line with the direct purpose of reducing the inductive effect from that line, and I can quite believe that there is a field for it on certain aerial lines and subterranean lines in order to silence those lines. On lines possessing great

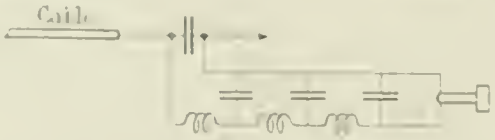


Fig. C.

resistance and capacity (S × R). I do not see how we can advantageously utilize this method. Take, for instance, a submarine cable. A signal sent into the cable crisp and sharp emerges at the distant end as a signal with a very long tail. That tail has to be lopped off before it can be utilized even for ordinary recorder working, and for relaying purposes the signal has to be accurately, well shaped, whilst for purposes of speeding the necessity for a good signal is further emphasized. It may be interesting to mention that a silencing method like that of the author was used in 1915 at one of the Stations of the Associated Cable Companies at the suggestion of the then Engineer-in-Chief, Mr. Judd, for the purpose of rendering duplex balancing a little more easy. Instead of connecting the receiving instrument direct to the bridge in the usual way, a device is inserted between the bridge proper and the receiving instrument in the form of a series resistance R, and parallel capacity S, as shown in Fig. B. Then a sharp, well-defined signal originating in the battery A arrives at the point D smoothed down by the action of the intervening S × R. The receiving instrument is therefore joined to D D′ instead of to C C′. At first sight this worked well, it eased the balance by eliminating high-frequency disturbances. But it was found that by the time the signal at the distant end was restored to its original size and shape, we were at the same time brought back to the conditions prevailing prior to the application of the silencing device. I mention this case as being the type of problem the author will meet with in applying his system to circuits possessing great time-constants. I may also mention that in a series of experiments

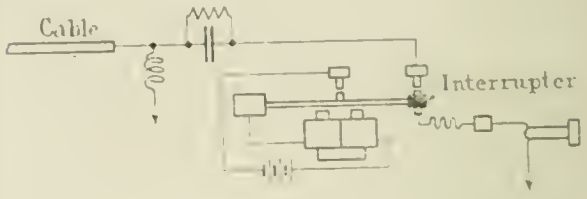


Fig. D.

carried out in the North of Ireland for Sir Oliver Lodge and the Post Office, silencing devices for the receiving instrument had to be resorted to. These consisted of a number of inductances and capacities arranged, in one form, as shown in Fig. C. For disturbances of constant frequencies the scheme was successful.

I may show here by means of Fig. D the connections in the scheme which Mr. Judd referred to earlier in the discussion as the means adopted by the Associated Cable Companies for emergency purposes. That also

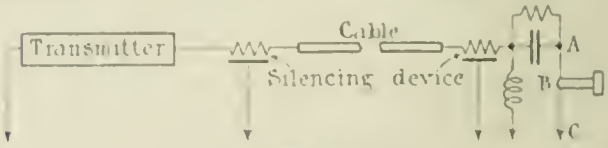


Fig. E.

worked splendidly, even on very long cables. If the author intends applying his silencing device to lines that have no great S × R he should proceed in the way shown in Fig. E. If we consider the signal shown by the author in Fig. 11, it will be seen that its shape is inconsistent with high-speed working. The silencing device shown in Fig. E produces in the line a distorted signal. This distortion is to a great extent eliminated by the shaping device at the receiving end. If the system is modified in that way I think there is a field for it on lines that are inductively troublesome. The interrupter is not shown in the figure. It is to be inserted between A and B, or B and C.

Mr. W. Gaye: I should like to express my regret that in this discussion more has not been made of the main object which the author had in view. Whether the fundamental principles underlying his scheme are new or old, I think the attenuated current that he endeavoured to work with, and his endeavour to keep his line free from high-frequency currents, were very well conceived and the whole thing carried out in a most resourceful and clever way.

Mr. W. J. Thorrowgood: I remember many years ago a large number of experiments that were made, some by myself, with a view to superimposing telephones and vibratory buzzing telegraphs on ordinary telegraph wires. Several systems have been successfully used, but it was common knowledge and a well-recognized fact that any conversation or telegraphic signals on such single-wire circuits could be heard or picked up on telephone receiving instruments; also, if secrecy was desired, that a double-wire circuit properly run would give the secrecy desired. It is a matter of regret, in view of the loss of life and damage done to our Army men, that our military authorities were not aware of these well-known facts, and that they were surprised that the Germans were reading their signals, but it is very possible that the Germans were also surprised that we gave them the opportunity. It would have been better had we caught the Germans. However, I think we must congratulate the author on having adopted these principles in 1916 and thus got over a very serious difficulty. The title of the paper mentions application to military and civil telegraphy. We have to remember that this system and the like have to be operated by human agency. Taking the case of land lines and private or semi-private companies who require inter-communication, I think the time has come when telegraph signals and signalling are out of date, and that we should lay stress on telephone communication between various places instead of telegraphs as at present. Telegraph communication can only be made by expert operators, who require to be thoroughly trained at considerable cost. The telephone requires no operator—anyone can use a telephone; conversation can be made over a telephone circuit at a very much greater speed than by telegraph. In the administration with which I am connected we are introducing telephony to supersede the telegraphs as much as possible. There is considerable difficulty in getting operators to take up the Morse code, and that is a great barrier to the use of telegraphy where there is a mixed business to contend with. The single-needle or Morse telegraphs are barriers to direct communication between principals, but telephones facilitate such direct conversation. I advocate the telephone and think it has many advantages over this or other telegraph systems, unless under special circumstances.

Brigadier-General A. B. R. Hildebrand: The author has mentioned my name in referring to the time when the Germans first started listening to our conversations. I think it is only fair to say that two French officers of the Tenth French Army were, as far as I know, the first people to intercept telegraph or telephone messages at the Front. They used ordinary wireless telegraph receivers and earths made of 75 mm. cartridge cases, and it was from them, I have always understood, that the Germans took up the idea. It was not because we thought the Germans were reading our messages that we took precautions, but because we knew the French were reading German messages, and it was then that the author worked out his scheme. There are, I think, some grounds for the prejudice against the instrument in the Army. When it was first introduced the instrument required considerable adjustment, an adjustment which the ordinary operator trained in the Army had not been taught and understood very little about. I think the Australian Corps were the first who really took up the matter properly. They appointed what they called inspectors, and whenever there was any trouble with the Fullerphones, these inspectors were sent to put it right. I cannot say that the Fullerphone will always work through a leaky line. It greatly depends whether the leak is near the sending instrument or not. Where the leak is near the sending instrument the very small amount of current sent out does not always reach the other end—or that was our experience. I cannot say that I tried it on earth return circuits to any great extent. We insisted on the Fullerphone being used on return metallic circuits. It was these little difficulties at the Front, under very bad conditions, with inexperienced men, that prejudiced operators against the instrument, and which would, I am sure, with better training be eliminated.

Brigadier-General Godfrey-Faussett: There is one remark in the paper which has not been dwelt upon at all in the discussion, and that is the question of using the Fullerphone as an exchange telegraph instrument. In the large offices on active service, such as the Army or Corps offices, it is found by practical experience that the amount of transmitted work is considerably greater than the amount of received and forwarded work combined, so it is obvious that anything which can be designed to save the number of operators employed in transmitting is an advantage, and I think the future of the Fullerphone is very promising in that direction. We were trying experiments of that nature with sounder instruments in France just before the Germans made their last attack, and unfortunately the experiments had to be stopped on that occasion because the particular place where they were being tried was one where the Germans advanced very strongly. It was sufficiently important to try it on the Morse, and I think the advantages of the Fullerphone in that particular connection are worth bringing to notice.

Mr. H. Wilson: With the exception of one point which may be of military interest, I propose to confine myself entirely to the civilian aspect of the Fullerphone. I have found that one of the Armies, with the object of preserving secrecy, employed operators with dialects at their switchboards, and I think that two Cornishmen, two Aberdonians, or even two men from my native Tyneside, would be able to produce something which would be very puzzling not only to the Germans, but to ourselves. Turning to the civilian aspect of the Fullerphone, we are at once faced with the question of buzzer working versus sounder working, and that seems

to me one of the most important points we have to consider. I think 90 per cent or even more of those who have any experience of the two systems, buzzer versus sounder, will say that the sounder working is much less trying than the buzzer. Even with good buzzer signals in the early days when we were experimenting with the Fullerphone so persistent are the buzzer signals that I could read buzzer signals quite easily when going home in the train at night. I have not the slightest doubt that if one asked the great majority of telegraph operators, they would immediately vote in favour of sound reading as being less trying and much more easily dealt with than the buzzer, apart altogether from the fact that with buzzer working one must of necessity employ headgear receivers. With regard to the advantages laid down in the paper, the first is great saving of battery power, but I think that is really more apparent than real. When we take into account that the telegraph offices of to-day must have large accumulator systems for other work, I do not think the balance in favour of the Fullerphone would be really appreciable. With regard to the simplicity of office wiring and the simplification of the instrument, I should like to ask the author, who recommends that for Fullerphone working the earth should be quite separate from the earth employed for ordinary Morse sounder, whether that means that in any large telegraph office the main "earth" provided there would not suffice for both Fullerphone and sounder. If we have to have a separate earth for each Fullerphone, instead of simplifying the wiring conditions, it would very greatly add to the complexity. Apart altogether from that, if we look at Fig. 13 as representing an ordinary Fullerphone station for civil purposes, we find two coils, three condensers, one special relay, an adjustable shunt, one local relay, one call buzzer—and a buzzer is the most unreliable instrument we have to deal with—and the chopper. I beseech the author to alter that last name. Taking into consideration the batteries and the various switches, and comparing it all with the simple polarized sounder, a mild condenser, and single-current key of a common battery set largely employed for communications for which the Fullerphone would be adopted, I think it will be admitted that the case for simplicity has not been made good. The next advantage claimed is that very long distances can be covered without translation or relaying. I cannot conceive that that is so. I think traffic considerations would make the use of Fullerphones intolerable from other points of view. With regard to the claim that maintenance of lines can be reduced to a minimum, surely we do not want to reduce the lines to a minimum, but to increase them as far as possible from the point of view not only of the Fullerphone but of other circuits. Also if there is a leakage taking place I assume it would cause confusion even in Fullerphone circuits. With regard to *g*, I think that is correct. With regard to *h*, the possibility of working long straight lengths of land line and then cable and land line again without any conversion or re-transmission, that of course is also possible, but traffic considerations would make it almost impossible to adopt any such thing as that. The introduction of impedance, to alter the wave-form, of course, reduces the speed capacity of the line, and it might not be possible to permit this. I agree with the author's conclusion that the scheme has many outlets for real good service, but it is a mistake to try to magnify or exaggerate the uses to which the Fullerphone might be put.

Mr. J. Eck: There are one or two questions I should like to ask. The author mentions frequencies between 300 and 700: has this any practical effect on the speed of receiving and the period during which an operator can receive without being befogged in his brain? I should like to ask the author if he could give us some particulars of Captain Turner's relay which seems likely to have a very important effect in the civilian application of this apparatus. It is to be regretted that the Government did not let their difficulties be known to engineers at large so that they could have given earlier assistance. One or two gentlemen were able to do it, but they did not probably realize what the troubles were.

Mr. Ll. B. Atkinson: Apropos of remarks which have been made, I may give the following experience. In the early part of the war a nephew of mine, a young fellow who had just left school and knew nothing whatever of the military arts or of electric science, wrote to me something as follows: "We have discovered that the Boche reads all our signals sent by the buzzer. As you know all about electricity, and as my Colonel has put me on to solve the question, would you kindly write to me how to do it?" It occurred to me, as it did to Mr. Eck, that it was a wonderful thing the Army needed to discover that if they stuck two bayonets into the ground and completed the circuit through the earth everybody within a reasonable distance would be able to read the message, and I also thought it was curious that they should apply to a boy just out of school who knew nothing about the subject to find a solution of the difficulty. I wrote back and said: "If you will send me the following information"—and I sent him a list of questions—"there are hundreds of people who can solve the question for you very quickly without the Colonel being troubled with it." His reply was: "I am forbidden to send you any of the information you ask for."

Lieut.-Colonel A. C. Booth: The Fullerphone has filled a want which was very greatly felt in the signal service at that time. Unfortunately, the discovery was not made early enough, and I think many lives were lost in the earlier days of the war before it became available. The buzzer is a favourite instrument in the Army, but a most aggressive instrument; it upsets everybody within its range and one cannot get away from it. The author has produced an instrument which disturbs nobody, and if one wants to hear one has to adopt the very latest type of apparatus to find it, and must get very close to the actual hut. Between those two extremes there are several other instruments which are much less aggressive than the old Army buzzer, and therefore less capable of being tapped. The ordinary sounder is one, and that I think was not used in the forward areas to the extent it should have been in the early days of the war. If they had

been used, their notes of induction being much the same by steady currents, a number of them would easily have confused any listening station, and overhearing to a large extent would have been prevented. There is another instrument known as the Wheatstone ABC that could have been used, and which is extremely difficult to tap, more especially if a number of them are in use There were some hundreds of these available, and it has been a mystery to me why they were not used at this particular time as a stop-gap between the ordinary buzzer and the Fullerphone. It was recommended on several occasions to the signal service, and perhaps the author can enlighten us as to the reason why they were not utilized. There are one or two criticisms of the Fullerphone that I should like to make, more in the way of constructive criticism, especially in regard to the facility for putting on a telephone. The *raison d'être* for the existence of the Fullerphone is that it should not be tapped, but the addition of the telephone is the most perfect means for enabling this to be done. To my mind it is like short-circuiting the thing. We all know that the regulations say the telephone shall not be used. My experience in the last five years is that regulations are mainly put up to be shot at. I have even known credit to be given in cases where regulations have been successfully overridden. One can easily imagine that the Fullerphone may not be liked by some operators. An officer may say: "If you cannot get him on that, go on to the telephone, it is only a few words"; but those few words may mean losing a battle, and I hope the author will have the telephone taken off. I am very disturbed about it altogether. Look at the number of cases of grenades brought home from the war exploding in houses. An indiscreet officer can easily say: "Pass that on the telephone," and the whole damage is done. With regard to the potentiometer, it is a very simple instrument for an ordinary electrical engineer, but when the average operator who has to maintain the adjustment of his instrument comes to look at the diagrams, well, he goes on to the next. Why have a potentiometer? If the earth currents are of little disturbance, and if one can reverse the line to earth to get over the difficulty, why is a potentiometer wanted? I like simplicity for those who are in trenches or in dugouts. I am mainly interested in the longer lines. The results which the author quotes on page 34 are very interesting, but he does not give the speed at which they worked; it may have been 6 words a minute; one remembers that the Old Army was satisfied with 10. Between London and Birmingham at the present time we work 180 words a minute each way, printed, and between London and Glasgow 120 words a minute each way, printed. That is a problem the author might like to look into. If he puts in chokes at the end of the line, the signal is flattened out, and the curve in Fig. 11 (*a*) would be all joined up as one. I do not know how he would get over that. In some cases of cables I have worked on, it is as much as we can do to get a Morse signal through without the signals running together.

Mr. W. Dolton (*communicated*): I should like to ask the author a question. During the past two years while engaged as an instructor on the Fullerphone in the Southern Command I gained a good deal of experience in various patterns of the apparatus, and towards the end of the summer of 1918 I obtained a diagram of the German instrument known as the "Utel," which, while it is in principle copied from the British Fullerphone, has one or two differences. For instance, instead of a make-and-break or chopper on the Fullerphone circuit, a small microphone mounted upon the reed of the local buzzer provides a varying resistance of musical frequency which answers the same purpose. It appeared to me that if this arrangement was equally satisfactory, that it had the merit of requiring less adjustment than the British pattern with its No. 1 and No. 2 contacts. Another feature was that the calling was effected by putting a steady current on the line which actuated a sensitive relay at the receiving station. This relay operated the local buzzer through a local battery. I understood also that the instrument was then being tested and examined in the Experimental Section of the Signal Service, and I should be very grateful if the author could give us the result of the investigations.

Mr. F. E. Meade (*communicated*): Referring to the theoretical diagram of the Fullerphone given in Fig. 4, the non-inductive property of the system depends on the action of the condenser K3. It is interesting to note that this condenser can only operate because the line current is not an absolutely steady one. Let the sending key at the distant station be held down, and the buzzer at the receiving instrument be running. At the moment of break of the contact, the line current begins to decrease and the potential difference across this condenser rises, the condenser taking a further charge. The line current during the small fraction of a second while the contact is open passes through the condenser as a displacement current. While the condenser is still charging, the contact is made again. The potential difference across the condenser now falls owing to the line current increasing to its former value. The condenser discharges to its former voltage, the discharge current assisting the line current in giving a pulse of energy to the receiver. The frequency of this variation of line current is the same as the buzzer frequency: its magnitude is very small, since a telephone receiver connected in series with the line is silent. No ripples are to be observed on the curve of line current shown in Fig. 11(*a*), but if there were actually no variation at all, then there would be no change of voltage across the condenser while the distant sending-key was depressed, and the condenser would be quite inoperative. The curve of line current shown in Fig. 11 is rather obscure. The idea conveyed by Fig. 11 is that the line current is so much smaller than the receiver current at normal voltage as to be immeasurable by the same means. The magnitude of the line current cannot be less than the average value of the current through the receiver. An earth current in relation to Fullerphone working may be either an end-to-end current that enters at the earth pin at one station and leaves at the other, there being no appreciable line leakage, or the earth current may enter or leave the system at places where the insulation

of the key is faulty. In some of the earlier types of Fullerphones the buzzer was at rest when the operator was sending, and a study of the circuits of the instrument given in Fig. 10 shows that when the buzzer is not running, the chopper contact being open and the sending-key at rest, there is no path for a steady current through the instrument. An end-to-end earth current would not affect the Fullerphone working, since for such a current the circuit is open when the key of the sending instrument is at rest, and when the key is depressed to send a dot or dash the earth current is simply added to or subtracted from the signalling current. It can always be arranged that the earth current increases the strength of the received signals, and with this connection, i.e. sending with the buzzer at rest, signalling has been carried on using earth currents alone. By having the buzzer running whilst sending, the operator has the adjustment of his receiving circuit constantly under test, and hearing the outgoing signals has been found to give confidence to an operator trained chiefly in ordinary vibrator working. The blurring effect of line capacity is also eliminated. Can the author state if there are other advantages? The second type of earth current, probably the one more frequently met with in military working, can only be completely eliminated by means of a potentiometer. The author says on page 32 how signals can be improved by increasing the resistance of the Fullerphone earth connection. This is often very effective in dealing with this class of earth currents in cases where a potentiometer is not available. The introduction of resistance in the earth connection has the effect of increasing the resistance of the local earth current circuit to a proportionally greater extent than the increase made to the resistance of the whole Fullerphone circuit. The earth current that passes through the instrument is therefore cut down to a larger degree than the line signalling current, and signals become correspondingly clearer.

Mr. E. S. Ritter (*communicated*): The author deserves great credit for the manner in which he has developed the instrument, which undoubtedly met a serious military need at the time it was produced. In my opinion the military authorities deserve a certain amount of censure for not making a want of this nature more widely known amongst those who should have been in a position to supply the want. One speaker has suggested that the Wheatstone ABC instrument might have been used as a stop-gap, or perhaps the Van Rysselberghe system using a polarized sounder of high resistance or an ordinary sounder and relay. The ideas underlying the instrument have been known for a long time, but it is to the credit of the author that he has put them together in the form of a good practical working instrument. On page 32 the author mentions that the Fullerphone is liable to be upset by leakage from a Morse circuit or a common "earth" with a Morse circuit, yet he states on page 31 that "From experiments and trials recently made it has been established that the Fullerphone can replace Morse sounder sets on *any* land worked line." This seems to be rather a sweeping statement in view of what was said on page 32. The author might reconcile these statements. The author might have mentioned a further advantage of the instrument on page 34, that of "portability." I take strong objection to the word "chopper" as applied to the local buzzer, and would suggest the word "interrupter" as being better and still describing the function of this particular piece of apparatus. In connection with the proposed use of the instrument for civil work I should like to make a few observations. The four fundamental points in the present instrument are: (1) The sending to line of a very weak current at a low potential. (2) The rate of change of this current is reduced to a minimum by means of choking devices. Consequently the working of the instrument is unlikely to disturb adjacent telephone or telegraph lines, including lines on which it may be superposed. (3) It is not itself disturbed by currents of telephonic speech frequency (or perhaps high-speed telegraph currents). (4) The reception of the signals aurally by means of a headgear telephone receiver. The uses of the instrument for civil work would appear to be strictly limited with the instrument in its present form. I here assume that the connections of either Figs. 13 or 15 are used. The principal disadvantages of the instrument as they appear to me are: (1) The susceptibility to disturbance from slowly-varying earth potentials such as might be caused by electric traction, etc., as well as adjacent Morse telegraph circuits. No doubt some of this trouble could be got over by using greater voltages or working on a metallic loop circuit. The first alternative increases the battery costs, the second the line costs. (2) In its present form it appears to be a low-speed hand instrument, and not suited to high-speed working. (3) The reception of the signals being on a headgear receiver may be objectionable in civil work. A loud-speaking receiver with or without an amplifier or some device working a sounder would perhaps get over this objection at the expense of simplicity. (4) The "interrupter" would appear to require occasional adjustment. Can this always be done by skilled operators, or has the author an absolutely reliable buzzer? I will now indicate one or two uses which the instrument could perhaps be put to with advantage. It could be used as a telegraph "speaker" to link up various testing offices and linemen's huts along a main underground or overhead route. It might be superposed on two loops of a loaded cable or even on two loaded phantom circuits. In both cases it would work on a metallic loop, and therefore be free from earth disturbances. It could also be superposed on a loaded cable loop or phantom circuit with an earth return or even used on aerial wire circuits. Linemen in search of faults might carry a portable set and could call up the testing point, using the instrument either as a telegraph instrument or as a telephone. Used in a testing office the objection to a headgear set would be a minimum, as the use would be intermittent. A second use for the instrument would be to replace Morse sounder circuits where for any reason they might be causing disturbance to telephone or other circuits. A third use, and one which I think the author had in mind when writing the paper, is to connect, in sparsely populated countries,

villages to towns some distance away. Here also the combination of the telephone with the instrument might prove of use. I should like to suggest to the author that he might consider the conversion of the set to central battery working for short distances and perhaps metallic loops. A steady current might be sent out which would work the " interrupter " at the out station. This current could be balanced as regards the receiving circuit by electrolytic cells or a potentiometer, the signals being sent and received by varying the strength of current flowing in the main circuit either by altering the resistance at the outer and home ends, or by altering the battery voltage applied at the home end. By these means it might be possible to work instruments off a telephone exchange battery. Contrary to the opinion I heard one speaker express, I should imagine a duplex balance could be easily obtained on account of the slow rise and fall of the current. Perhaps the author has some experience on this point. On the other hand, if the line insulation is poor and varying, a duplex balance, if not impossible of attainment, might be extremely difficult.

Major A. C. Fuller (*in reply, communicated*) : In reply to Mr. Judd, double-current working can be and has been used for Fullerphoning. The potentiometer, severely criticized by some speakers, can easily be arranged to balance out the effect of the spacing currents, and therefore automatically doubles the effect of the marking current. In many of my high-speed recording experiments where Fullerphones with their small line currents were employed, double-current working was successfully resorted to. There is no good reason known to me why the inverse-current method described should not be applied to the Fullerphone. As explained in the paper the investigation of the use of the instrument and its capabilities over long submarine cables has not been carried very far, but the author would be very pleased to have an opportunity of seeing what could be done in this direction.

I am in agreement with Colonel Evans in general. At the same time I should like to point out that my early design of instrument for the Front did include the potentiometer, which was ruled out by higher authorities partly for the sake of simplicity and partly, I believe, to hasten supply. Experience, however, confirmed the desirability of including the potentiometer, and it was again introduced into the later models.

I think it will be conceded that Mr. Harrison attributes to me more sanguine views than I have ever expressed. Reference to the " conclusion " of my paper will show that I never contemplated " the universal employment of the Fullerphone in civil telegraphy." I still hold to the views expressed in the paragraph referred to, and it is therefore not necessary to deal further with this speaker's remarks on this misapprehension. It may be of interest to remark that duplexing experiments have been successfully carried out. Again, Mr. Harrison speaks very confidently of various disturbances which are commonly met with " hopelessly jamming the apparatus "—to this I can only reply that perhaps his experience of this has been both larger and more unfortunate than mine, since I have only very rarely met or heard of a case where this jamming occurred.

Since Mr. Brown's device which he claims to be similar and prior to the Fullerphone was on his own showing " made principally to work through broken wires or cables," there must be some radical difference between it and the Fullerphone, for the one condition for which the latter is useless is that when the conductor is entirely broken. I entirely agree with Mr Brown that at first sight his system appears to include no wave straightener, and further it actually has none and would not properly fuuction, as the Fullerphone does, over the lines on which the Fullerphone was designed for and worked over. Mr. Brown appears to fall into the error (which is common to many others) that the only earth currents to be feared are those originating at the ends of the line. This is not the case. Further, where, as in war, the instruments have to be used exposed to weather and in wet positions such as dugouts, the bottoms of trenches, etc., their insulation suffers, and I am of opinion that to balance the inevitable earth current is far sounder than to assume that it can be prevented. Though no doubt the action of the War Office in 1897 was disappointing to Mr. Brown, I think that since the War Office were not administering long submarine cables their action was at least defensible. Why did not the speaker put forward his device in 1914 ? The latter portions of this speaker's remarks are too vague to deal with, and in any case do not seem relevant to the discussion.

Mr. Nash throws an interesting light on the transition stage between the use of the vibrating system and the introduction of Fullerphones. The screening methods outlined were without doubt of great value as a stop-gap. They could not, however, be retained for various reasons, among which two may be mentioned, viz. : (*a*) The expenditure of energy (battery power) and line maintenance involved ; (*b*) the method not only jammed the enemy listening-sets, but also jammed certain of our own important communications. I should like to express my gratitude to this speaker for his sympathetic feeling towards the author of the paper.

General Hildebrand's remarks go far to answer Mr. Thorrowgood's opening. There is no doubt whatever that the Allied military authorities were quite alive to the fact that messages could be overheard to some extent, as were the other belligerent Powers. The matter only became serious, however, with the development of the amplifying valve which occurred during the early stages of the war. It appears to be still taken for granted in civilian circles that the technical military authorities were, and perhaps still are, behind their civilian confrères. This impression should I think be erased. The fact that military scientific development is of necessity frequently carried on behind a screen and without publicity should not be overlooked. To return to General Hildebrand's remarks, it is worth noting that we at home reproduced as many of the cases in which failure to get through bad lines had occurred as we were able, and we were always able to work. From this I think we can safely assume that the insufficiently trained personnel was to blame rather than the system.

It is to be regretted that the interesting trials being carried out in France were interrupted by the German advance. I hope, however, that General Faussett will see his way now to carry on these experiments under more stable and satisfactory conditions.

Mr H. Wilson opens up the controversy of reading buzzer versus sounder signals. Mr. Wilson is very much in favour of sounder signals, and this fact alone makes me confident that he was trained first to these signals. I find that the telegraphist—and I have had a fair experience of them—is very faithful to his first love. Those taught on sounder prefer sounder, those taught on buzzer prefer it. Hence as the greater number of telegraphists to-day (at any rate P.O. telegraphists) were sounder reared, so their opinion would doubtless favour the sounder.

As in the case of a former speaker, I find in Mr. Wilson's remarks evidence of misapprehension of my ideas of the future use of the system. May I quote again from my "Conclusion": "For civilian use, one cannot expect sounder sets that are established and giving satisfaction over well-constructed routes to be discarded in favour of Fullerphones; but it is expected that the advantages to be derived from the new system will lead to its adoption in countries not already thoroughly developed from a telegraphic standpoint. An opening should also arise in tropical countries where maintenance difficulties are considerable—and it is probably not too much to say that the system described would give satisfaction wherever difficulties from any cause render Morse sounder working precarious." Certain telegraph engineers—more especially those of the British Post Office—seem to have their vision limited to the extent of the British Isles. Why, for example, does Mr. Wilson say that "the telegraph offices of to-day must have large accumulator systems for other work"? Is he not mentally contemplating the G.T.O. London, the Office in Liverpool, or some similar large city in a densely populated area? What of a telegraph office in the Argentine—or even in rural Canada—in the vast spaces of China, or in some Russian village? Why must they have "large accumulator systems," and how are these accumulators to be charged? I specifically state in the paper that I do not expect the Fullerphone to displace established systems, and I clearly conceived its use in such localities as above indicated, yet Mr Wilson says: "It is a mistake to try to magnify or exaggerate the uses to which the Fullerphone might be put." I quite agree, but surely the magnification and exaggeration have been employed by others, in order to have something almost ridiculous to criticize. A similar case of apparent misapprehension is contained in the following passage from Mr Wilson's remarks: "With regard to the claim that maintenance of lines can be reduced to a minimum, surely we do not want to reduce the lines to a minimum, but to increase them as far as possible." Cannot Mr Wilson differentiate between reduction of maintenance and reduction of lines? Again reverting to an earlier remark of Mr Wilson's, he says: "If we have to have a separate earth for each Fullerphone, instead of simplifying the wiring conditions, it would very greatly add to the complexity." Let me reply that the paper was meant to convey the information that where there were Morse sets and Fullerphones working in the same office there should be two, and only two, earths—one for the Morse sets and one (common earth) for the Fullerphones.

Mr. J. Eck asks whether the note of the received signal has any effect on the speed of reception or the fatigue of the operator. The notes that can be obtained are quite satisfactory for any manual speed of sending. Individual operators choose different notes, but it is generally conceded that the higher notes give clearer and more definite signals, but at the same time are more tiring if prolonged reception is required.

From my experience of the conditions of lines in the early part of the war I am very doubtful whether it would have proved possible to have worked with the instruments referred to by Colonel Booth. At all events, considering the very leaky condition of cables, the expenditure of battery power would probably have been prohibitive. My views were not asked at the time, and I did not know of the recommendations referred to by Colonel Booth, so that I am afraid he must seek enlightenment elsewhere. With regard to the results quoted on page 34, these were taken as indicated in the paper from Official Post Office reports by the Research Department. No mention of speed was made, but probably the report referred to ordinary manual operation. As a matter of interest we have sent messages by Fullerphones on a loop from Woolwich to Bristol and back and recorded them at speeds between 60 and 80 words a minute, using the normal voltage and valve relays. I should very much like to know what grounds the speaker has for saying that the Old Army was satisfied with 10 words a minute, especially as he infers from the context that this refers to established communications over long lines. Is it beyond his knowledge or memory perhaps that the Old Army used standard Wheatstone apparatus with which (while not printing) it was customary to record at greater speeds than the 180 words a minute he refers to?

I wish Mr. Dolton had enlarged rather more on his experience of two years' work with the system. Unfortunately I have not had opportunity to investigate thoroughly the German pattern of instrument, but so far as I am able to give an opinion it is that the use of the variable resistance (i.e. the vibrating microphone) gives an even more secret system and does reduce adjustment. I do not think, however, that the instrument would work nearly so well over bad lines. As regards the calling by direct current, this has certain obvious advantages and has been adopted, with improvements, in the newest Fullerphones. I cannot agree that the German relay was sensitive. It was a very ordinary cheap relay, and I believe from the design of the set that the Germans only used them on short lines of fairly good insulation.

I think Mr. Meade's interpretation of Fig. 11 is the correct one. At the same time the average current through the receiver may be very minute indeed. There can only be current at the moment of contact of the interrupter, and the duration of contact may well

be only a small fraction of the total time of reception. Hence the instantaneous value of current may be relatively large while the average current is very small. The chief object of running the buzzer during transmission was, as the speaker suggests, to allow the operator to hear his own signals and so give him confidence. His hearing them is really no guarantee that his signals are going out, for he would hear them just the same with no line or earth. I am glad to find someone to say a good word for the potentiometer, and it is a matter of regret that none of those who had practical experience of the system in the field actually gave the result to the Institution during the discussion.

The statements referred to by Mr. Ritter do require reconciling. I admit that without careful insulation between circuits there is a liability to have trouble from leakage when Morse sets and Fullerphones work in the same office. What I mean by saying that Fullerphones can replace Morse sets on any hand-worked line is that, considering the particular line as an isolated case, even if it is difficult to work with Morse sets it can be satisfactorily worked with Fullerphones. I do not advocate putting a Fullerphone circuit among a large number of Morse circuits along the same route. In such a case the insulation must be good, and the Fullerphone should have a separate (and inferior) earth.

THE OSCILLATORY VALVE RELAY: A THERMIONIC TRIGGER DEVICE.

By Captain L. B. Turner, M.A.

(*Paper received 3 June, and read at a* Wireless Sectional Meeting *of* The Institution *30 June, 1919.*)

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1. Introduction. Relays, Triodes, Amplifiers.

The nature of the instrument forming the subject of this paper will be grasped more easily after a preliminary inquiry into what precisely is signified by the term relay as contrasted with the term amplifier. In wire telegraphy the relay plays a very prominent part, and the telegraph relay of to-day, as exemplified by the Post Office standard polarized relay, is a highly perfected and very familiar instrument. Its function is usually that of an automatic switch, whereby the arrival of a relatively feeble signal is made to close or open the circuit of a local battery competent to perform tasks for which the power of the incoming signal is insufficient. The local current is started or stopped by the signal current, but is not otherwise measured by it. There is a threshold strength of signal, below which no local effect is produced, and above which an effect is produced whose magnitude is independent of the strength of the controlling signal.

Amplifiers, unlike relays, have not until recently had a widespread use. Perhaps the Heurtley hot wire and the Brown microphonic contact instruments are the best known. But with the introduction a few years before the war of the three-electrode thermionic tube (De Forest, Lieben-Reisz), and especially with the subsequent introduction of tubes depending on pure electron discharge (Langmuir) and various ingenious methods of using them (mainly evolved by the French), electric amplifiers have suddenly assumed immense importance in wireless telegraphy and are destined in the near future to find the most widespread application. In view of the restricted popular knowledge of amplification by the so-called valves—or "triodes," to adopt the term recently suggested by Dr. Eccles—and because it is pertinent with them to proceed to an understanding of the particular device to be here described, let us briefly look into the *modus operandi* of the ordinary triode, without touching the ulterior physics of the subject), and distinguish it from that of a relay as defined above.

Fig. 1 shows a triode of a pattern produced by the French early in the war at the "Telegraphie Militaire." Here F is the "filament," a tungsten wire brightly incandescent; G is the "grid," an open helix of nickel wire concentric with the filament; and A is the "anode," an outer concentric cylinder of nickel. These are supported in a glass bulb exhausted to the best obtainable vacuum, or at least much better than that of the ordinary electric lamp. Triodes of this pattern

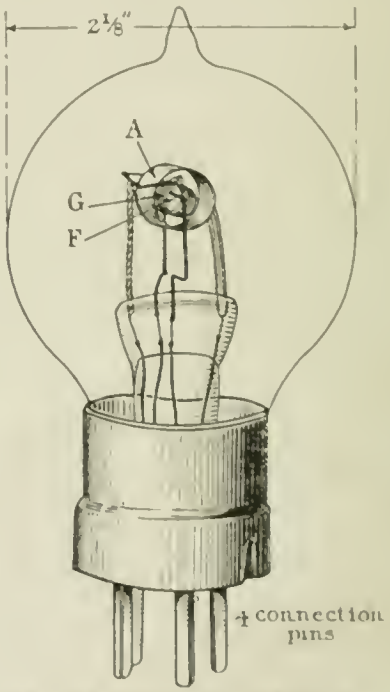

Fig. 1.—A common pattern of triode.

were designed to be fairly well suited to a great variety of uses; and the consumption of them by the French and British during the war must have run into a good many hundreds of thousands.

If the anode is maintained at a fixed potential v_a above the negative end of the filament (as by short-circuiting the resistance R in Fig. 2), and the potential v_g of the grid is varied, the anode current i_a is found to vary as shown by the curves in Fig. 2, each of which refers to a different constant value of v_a. Over the steep straight parts of the curves we have large changes of anode current in a high-voltage circuit

produced by small changes of potential of the grid. The relation is a linear one expressible as :—

> Increment of anode current equals a constant g times the increment of grid potential producing it ; or

$$\frac{\partial i_a}{\partial v_g} \cdot \hat{c}\, v_g = g\,(\hat{c}\, v_g).$$

Inspection of the curves shows further that an increment of anode potential also produces an approximately

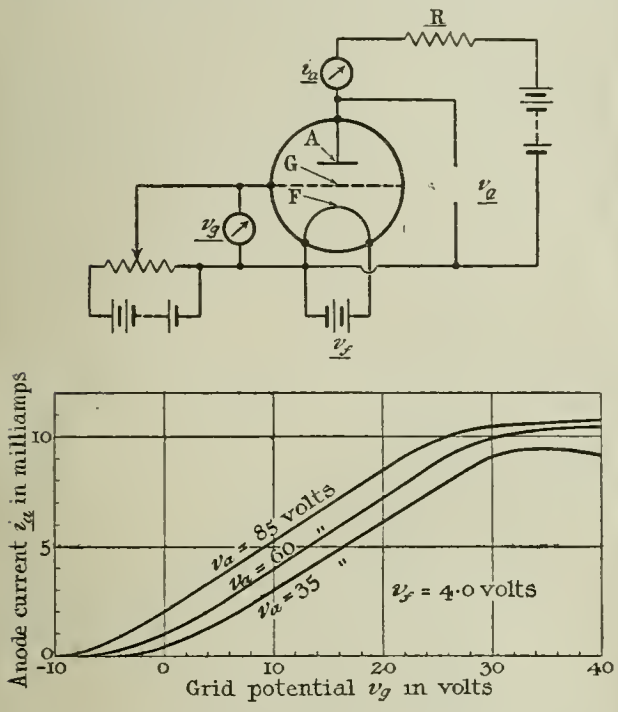

Fig. 2.—Triode characteristics.

proportional increment of anode current, the relation being similarly expressible as

$$\frac{\partial i_a}{\partial v_a} \cdot \hat{c}\, v_a = a\,(\hat{c}\, v_a).$$

Hence we may write

$$\hat{c}\, i_a = g\,(\hat{c}\, v_g) + a\,(\hat{c}\, v_a).$$

Now in the circuits of Fig. 2 a rise of anode current produces a fall of anode potential equal to the ohmic drop in the resistance R ; so that

$$\begin{aligned} \hat{c}\, v_a &= -\,\mathrm{R}\,(\hat{c}\, i_a) \\ &= -\,\mathrm{R}\,g\,(\hat{c}\, v_g) - \mathrm{R}\,a\,(\hat{c}\, v_a) \\ \therefore \frac{\hat{c}\, v_a}{\hat{c}\, v_g} &= -\,\frac{\mathrm{R}\,g}{1 + \mathrm{R}\,a} \end{aligned}$$

As R is increased so as to become very large compared with the anode resistance $1/a$, this amplification ratio approximates to g/a. In the pattern of triode we are considering,

$g = 0{\cdot}3$ milliampere per volt,
$a = 0{\cdot}04$ milliampere per volt

approximately, so that amplifications up to 8 may be obtained.

Such a device has sometimes been designated a thermionic relay, but this is an undesirable use of the term relay, for there is a very clear distinction between its performance and that of a relay as already described. Here there is no threshold effect, the smallest incoming signal producing some change in the local circuit ; and the local circuit effect is a magnified copy, more or less true to scale, of the incoming signal. The distinction between relay and amplifier is a useful one, and should not be allowed to disappear.

2. Principle of the Valve Relay.

Various methods of grouping several triodes, each functioning more or less in the manner described above, have been evolved, and amplifiers suitable for frequencies ranging from units to millions of periods per second have been constructed. They stand out from the earlier amplifiers, in which the velocities of molar masses instead of electrons must be controlled by the

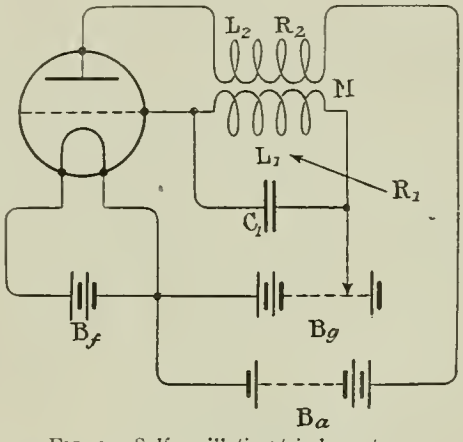

Fig. 3.—Self-oscillating triode system.

signal, in the smallness of the input powers which can usefully be dealt with.

The Oscillatory Valve Relay is a relay, not an amplifier ; but it depends on a triode as the link between the "in" and the "out" circuits, and consequently shares with modern amplifiers something of their extraordinary sensitivity, robustness, and flexibility as to frequency of operative signal current.

In the light of the elementary theory already set forth (Fig. 2), let us consider the circuits shown in Fig. 3. It is easy to see in a rough fashion without resort to accurate analysis, that under suitable conditions such a system becomes self-oscillatory, drawing the necessary energy from the battery B_a in the anode circuit. For suppose the circuit L_1 C_1 is set into its free oscillation, however feebly, such that approximately

$$p = 2\,\pi\,n = 1/\sqrt{(L_1\,C_1)}.$$

Then if R_1 is small compared with $p\,L_1$, and if $p\,L_2$ and R_2 are small compared with the anode resistance $1/a$, there is a quadrature electromotive force $p\,L_1\,i_1$ in the grid circuit producing in the anode circuit an alternating current $g\,p\,L_1\,i_1$ also in quadrature with i_1. With mutual inductance M (of the right sense)

between the two coils, there is induced in the grid coil an in-phase electromotive force $M g p^2 L_1 i_1$. If this is equal to the energy-consuming constituent $R_1 i_1$ of the electromotive force in the $L_1 C_1$ circuit, energy losses are just compensated and the oscillation persists unchanged in amplitude. The critical condition

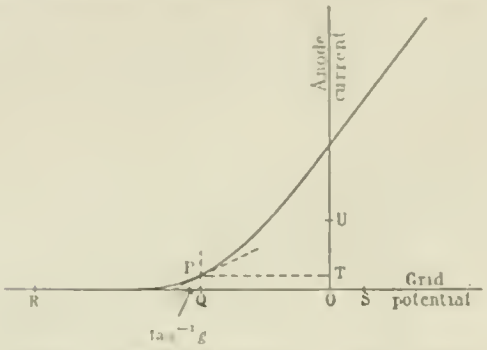

FIG. 4.—Inception of oscillation in Valve Relay.

for an infinitesimal oscillation, when once started, to persist unchanged is thus

$$M g p^2 L_1 i_1 = R_1 i_1$$

$$g = \frac{R}{M p^2 L_1} = \frac{R_1 C_1}{M}$$

If g is less than this critical value, a small oscillation cannot be self-sustaining; if g exceeds the critical value, any oscillation, however small, will increase in amplitude

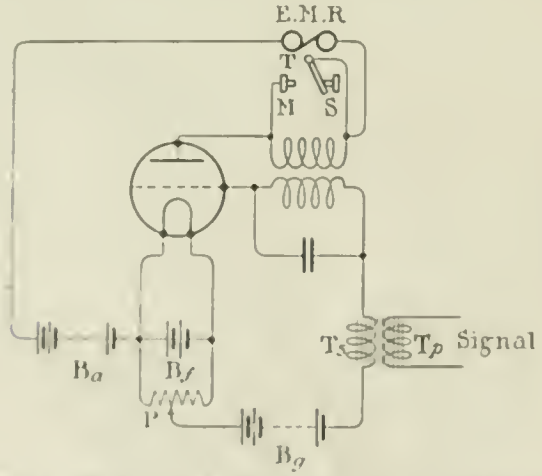

FIG. 5.—Circuits of Valve Relay for low-frequency signals.

up to an equilibrium value at which the losses in the triode circuits are equal to the power supplied from the high-tension battery B_a.

Suppose in Fig. 3 the grid potential is gradually increased from a low value by moving the slider on the grid battery B_g towards the left. The value of the parameter g, which is the slope of the curve at the representative point (Fig. 4), gradually increases until it reaches the critical value $R_1 C_1 / M$. Let O Q be the critical grid potential. At this point oscillation sets in, and is built up to some such amplitude as Q R, Q S, the anode current changing suddenly from the steady value O T to a pulsating current of mean value O U. The oscillation once set up persists, even though the mean grid potential be reduced much below the threshold OQ.

Fig. 5* is an extension of Fig. 3 showing how such an arrangement may be utilized as a self-restoring relay adapted to be operated by signal currents of frequencies of the order of hundreds or thousands of periods per second. The grid potential is finely adjustable on the potentiometer P; and when it is set a small amount, called the "margin," below the critical value, called the "threshold," any signal applied to the transformer $T_p T_s$ producing in T_s a momentary electromotive force of the right sense and exceeding the margin in amplitude, sets the system into oscillation. The accompanying rise of current in the coils of the electro-mechanical relay E.M.R. (ordinary telegraph relay) pulls over the tongue T, short-circuits the anode reaction coil, and thereby quenches the oscillation, which is thereupon only re-

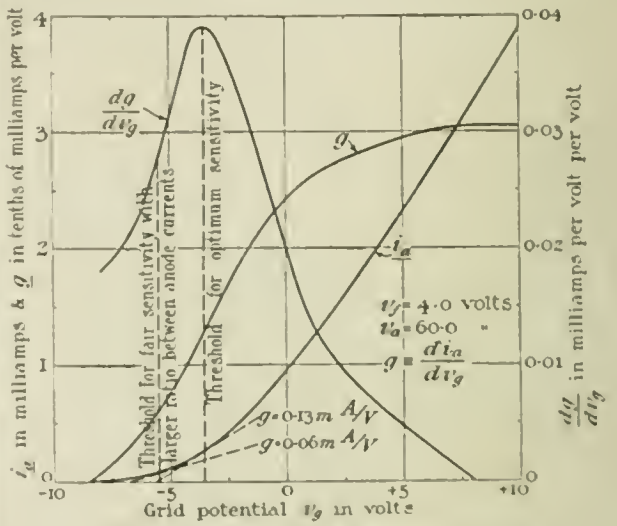
$\frac{dq}{dv_g}$
g
$-i_a$
Threshold for fair sensitivity with larger ratio between anode currents
Threshold for optimum sensitivity
v_f = 4·0 volts
v_a = 60·0 "
$g = \frac{di_a}{dv_g}$
g = 0·13m A/V
g = 0·06m A/V
i_a in milliamps & g in tenths of milliamps per volt
$\frac{dq}{dv_g}$ in milliamps per volt per volt
Grid potential v_g in volts

FIG. 6.—Method of choosing threshold potential.

(Enlargement of middle curve of Fig. 2 with two derived curves.)

ignited on the arrival of another signal in the transformer primary T_p. The opening of the contact between T and S may be used to control any indicating or other relaying apparatus.

As long as the grid potential remains above the threshold, whether by appropriate setting of the potentiometer or by a sustained incoming signal, the tongue T will chatter against the marking contact M. To ensure a steady clean break at S, it is convenient to arrange, by a suitable shunt across the magnets or otherwise, that the tongue while chattering against M does not travel far enough to touch S.

In the form of Valve Relay sketched in Fig. 5 we are not interested in the frequency of the oscillation; we are concerned merely to arrange that the incidence of oscillation shall be marked by a conveniently large

* In this and some subsequent theoretical diagrams, certain condensers necessary merely as shunts for high-frequency currents and obvious to anyone accustomed to high-frequency work, are not shown, as their omission simplifies the diagrams considerably.

rise of mean anode current. For several reasons, however, it is convenient to make the frequency high, or at least enormously greater than frequencies of the order of those of the signal currents. For sensitivity it is obvious that the signal electromotive force producing the rise of grid potential above the threshold should be sustained during many periods of the incipient oscillation ; and a relatively high frequency is also convenient in that the high-frequency currents can be shunted wholly away from the transformer T_p T_s so that changes in the external circuit may be without effect on the threshold. In the Valve Relay described in the next section the frequency is about 4×10^6 periods per second.

As already shown, the threshold potential is that at which the slope g of the characteristic (Fig. 4) is $g = R_1 C_1/M$. The triode and its batteries having been selected, we are still able to determine the critical value of g by suitable choice of R_1, C_1 and M, and the question presents itself of what is the most propitious region of the characteristic at which to work. From the explanation accompanying Fig. 4, it is clear that a large rise of anode current at oscillation is obtained only if the threshold P is well down to the foot of the concave portion. It is possible, however, to go too far down. Since the inception of oscillation is brought about by increase of slope g at the representative point, and since the increase of slope is effected by rise of grid potential, the best combination of sensitivity and stability is obtained when the slope varies most rapidly with the potential. We want

$$\frac{d\,g}{d\,v_g} \equiv \frac{d^2\,i_a}{d\,v_g^2}$$

to be large. In Fig. 6 the foot of one of the three curves of Fig. 2 is enlarged, and its second derivative relating $d^2\,i_a/d\,v_g^2$ with v_g is obtained. This derived curve shows that the best sensitivity is obtained here when the threshold is made to occur at $-3\frac{1}{2}$ volts. But no fine choice is necessary, a fair value of $d\,g/d\,v_g$ obtaining over the range of, say, $-5\frac{1}{2}$ to $-2\frac{1}{2}$ volts. In order to get a large ratio between mean anode currents before and after oscillation has set in, it is well to choose a threshold rather further down the foot of the curve. Thus a suitable compromise in this case might be $-5\frac{1}{2}$ volts. The mean anode current would then jump from 0·08 milliampere before, to perhaps 2 milliamperes after, the arrival of the operative signal.

3. A Valve Relay for Acoustic Frequencies.

Fig. 7 is traced from a photograph of a Valve Relay designed for signals of acoustic frequencies, containing its own grid and anode batteries and requiring externally only a 4-volt battery for the filament. Its connections and working instructions are shown in Fig. 8. It is provided with a small electric lamp as an indicator, together with a change-over switch allowing any external apparatus to be substituted for the lamp. It was designed to replace the ordinary telephones used to read Morse signals from a wireless receiver, or over the wire of an ordinary buzzer field telegraph set. It may of course be used after an interposed amplifier, but without any amplifier it is sufficiently sensitive to respond to signals only strong enough for comfortable commercial work, such as are said in Army notation to be of strength " R7."

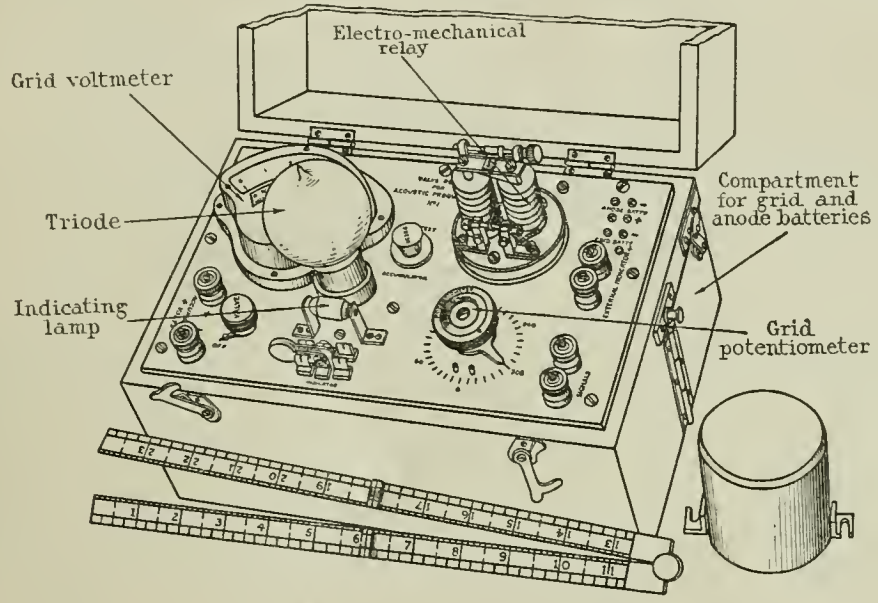

Fig. 7.—A Valve Relay for acoustic frequencies.

This Valve Relay is on the table, and can be connected to a source of alternating current of about 800 periods per second and of controllable strength. By switching the signals from appropriate telephones to the Valve Relay, those who wish will be able to judge of the sensitivity for themselves. A more spectacular

demonstration of the smallness of the energy required to trip the relay is provided by connecting an ordinary microphone with transformer and 2-cell battery, as the signal current bears no relation to the frequency of the oscillation set up. Such a type is well adapted to acoustic frequencies, because it is feasible to build

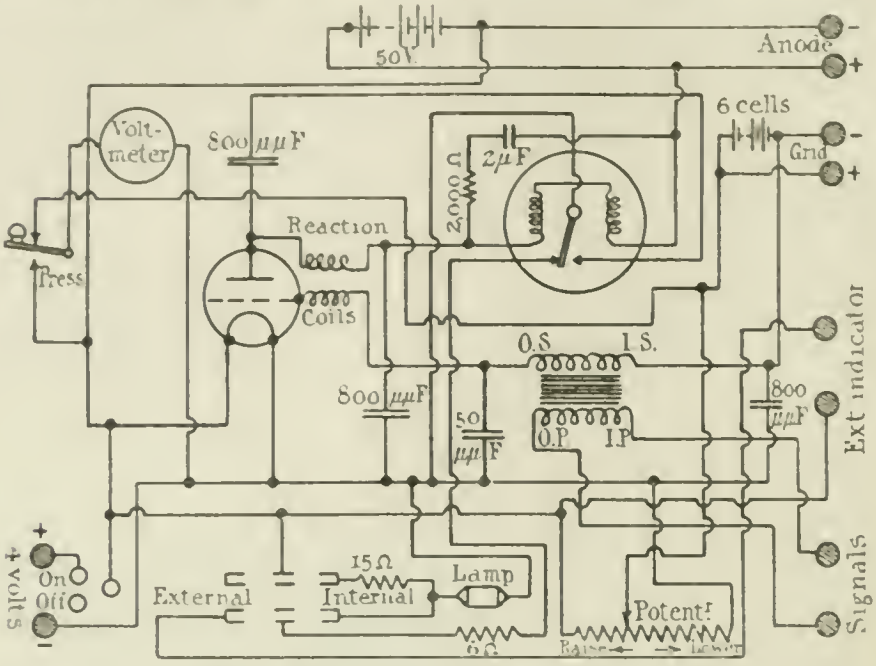

FIG. 8.—A Valve Relay for acoustic frequencies.

INSTRUCTIONS.

1. This Valve Relay is suited to take the place of high resistance phones [Brown 2 v 4 ohm Ω] in which strength of signals exceeds R[illegible]. Signals thus actuate the group [INTERNAL INDICATOR] or any instrument controlled by another relay connected to terminals marked EXTERNAL INDICATOR.
2. [illegible] Set Indicator Switch to INTERNAL. Move potentiometer towards RAISE until relay tongue chatters and lamp lights. Extinguish by lowering potential a little [with Voltmeter]. A corresponding signal producing on grid a rise of potential exceeding 1 volt then lights lamp to light.
3. Contact setting [illegible] should not be too tight. Fixed contacts should be only slightly open but enough to prevent lamp from flickering under telegraph signals.
4. Grid potentiometer indicates battery running down—probably accumulator which is tested by pressing button. Discharge of grid battery is regulated by anode battery to about 1 mA or 0.1 mA according as relay tongue is or is not chattering.

the source of signals. The microphone is provided with a small trumpet, and the relay will respond to a clap of the hands or a shout in any part of the lecture theatre.

Telephone engineers will be able to form an estimate of the power of the steady incoming signal sufficing to operate this instrument. It is of the order of 10^{-8} watts. Telegraph engineers, on the other hand, are aware that an ordinary Post Office telegraph relay, of the type which is embodied in this instrument and is controlled by the anode current of the oscillating valve, requires an operative power of at least 5×10^{-3} watts for reliable working even at low speeds. So that there is a power step-up of at least 5×10^5 times. Nor is there any need to restrict the power controlled in the anode circuit to such a small value.

As to robustness the war has proved the high-vacuum triode to be an instrument adapted for unskilled use in the field of battle. And the only adjustment in this instrument is that of a potentiometer to regulate the potential of the grid to a tenth of a volt or so.

4. Form of Valve Relay for High-frequency Signals.

The relay we have examined may be said to be of aperiodic or non-tuned type in that the frequency of the signal current bears no relation to the frequency of the oscillation set up. Such a type is well adapted to acoustic frequencies, because it is feasible to build for such frequencies quasi-aperiodic transformers capable of producing on the grid (whose impedance is sensibly

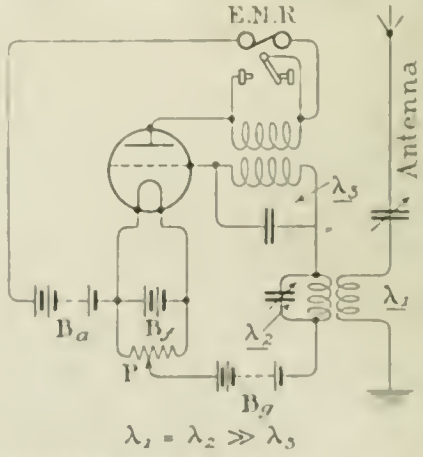

FIG. 9.—Circuit of Valve Relay for high frequency signals.

infinite at such frequencies) a large rise of potential with an expenditure of only minute power. If the aperiodic iron-cored transformer is replaced by suitable

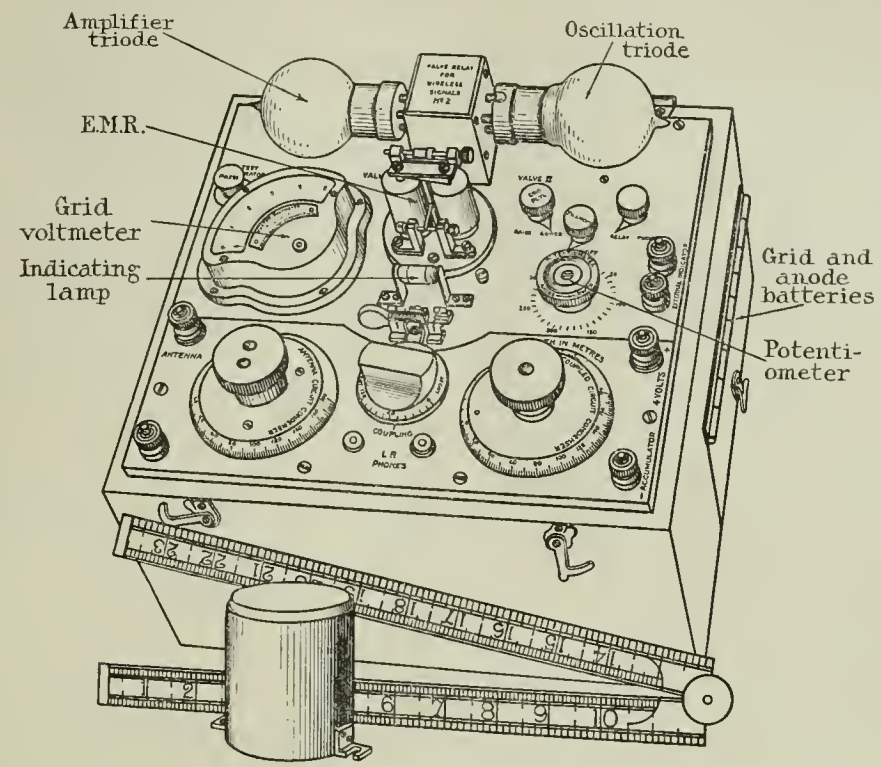

FIG. 10.—A Valve Relay for wireless signals.

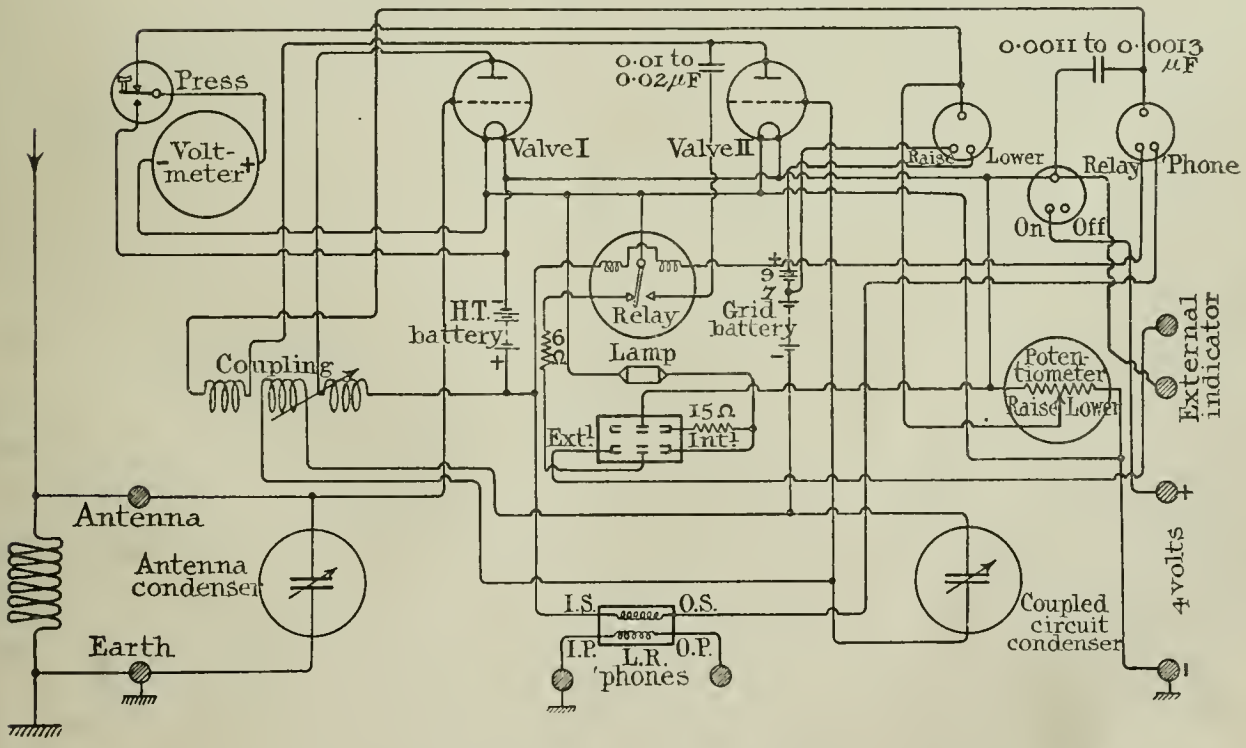

FIG. 11.—A Valve Relay for wireless signals.

1. This Valve Relay is suitable for C.W. or spark signals of about 1,300–3,200 metres wave-length.
2. When tuning up, set switch to PHONES; raise grid potential (by switch and potentiometer) enough to cause Valve II to generate; and tune in for signals in phones, making final adjustment of antenna condenser with loose coupling.
3. Switch over to RELAY; tighten coupling; and reduce grid potential until relay just ceases to chatter. Readjust coupled circuit condenser (very slightly only), and grid potential.
4. Minimize jamming by having loose coupling.
5. Change of coupling, but not of grid potential, may necessitate slight readjustment of closed circuit condenser; but not of antenna condenser.

tuned high-frequency circuits whose frequency is, however, still much below that of the oscillation generated in the relay, a relay of like sensitivity, but for high-frequency instead of acoustic-frequency signals, can be constructed. Such a relay for wireless signals is sketched in Fig. 9.

But where high-frequency currents such as those of wireless telegraphy are required to operate the relay, particularly if these are undamped or "continuous wave," an immense advantage accrues from tuning the oscillation-generating circuits of the relay to the frequency of the operative signals. Sensitivity is greatly enhanced, and there is added the possibility of an exalted selectivity as between signals of unequal frequencies and between signals of the same frequency but unequal decrement (see Section 7). The λ_2 circuit of Fig. 9 is then conveniently omitted, the λ_1 and λ_3 circuits are coupled together, and λ_3 is made equal to the wave-length λ_1 of the antenna and the incoming signal. To prevent the antenna being set into violent oscillation by the relay (as well as to obtain additional sensitivity), one

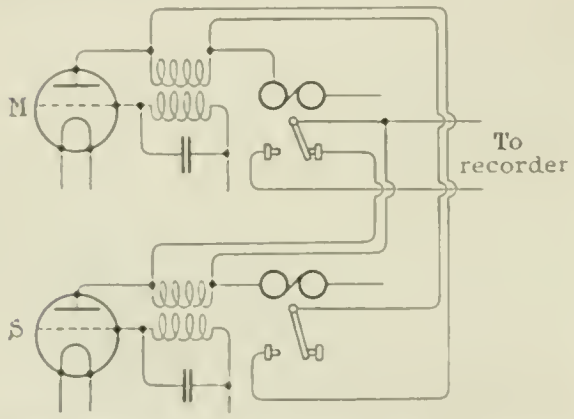

Fig. 12.—Interquenching circuits for double Valve Relays.

or more amplifying triodes may be interposed between antenna and relay.

It should be noticed that the high-frequency Valve Relay, unlike other wireless receivers, embodies neither heterodyne nor rectifier.

5. A Valve Relay for Wireless Signals.

A valve relay receiver designed for wave-lengths of 1,500–3,000 metres, containing its own grid and anode batteries, and comprising one high-frequency amplifying triode, is shown in Fig. 10, which is traced from a photograph. Fig. 11 shows the complete connections and provides sufficient explanation of the instrument.

The Valve Relay is, by movement of a switch, converted into an ordinary autoheterodyne receiver, and is used as such when tuning up to a continuous-wave signal, the final tuning being to the "silent space," i.e. to zero beat frequency. On then switching over from "phones" to "relay," and adjusting the potentiometer to a potential just below the threshold, we are left with a circuit exactly tuned to the incoming signal and of nearly zero decrement. The discrimination between C.W.* and spark signals (dealt with theoretically in Section 7) observable with this simple instrument is very striking. Thus a spark station of nearly the same wave-length as a desired C.W. station, and strong enough to jam the latter hopelessly as an autoheterodyne receiver, can be made innocuous for reception on the Valve Relay.

The instrument on the table is connected to an antenna on the roof of this building, and is shown recording the Morse signals A B C A B C from a small C.W. transmitter on Woolwich Common. A change-over switch allows a hooter to be substituted for the Wheatstone receiver, so that the signals may be read by all present.

6. Valve Relay for Steady or Slowly Varying Currents.

In the two forms of Valve Relay already described, the signal current was alternating or intermittent and produced the requisite rise of grid potential by the simple mediation of some form of transformer. For

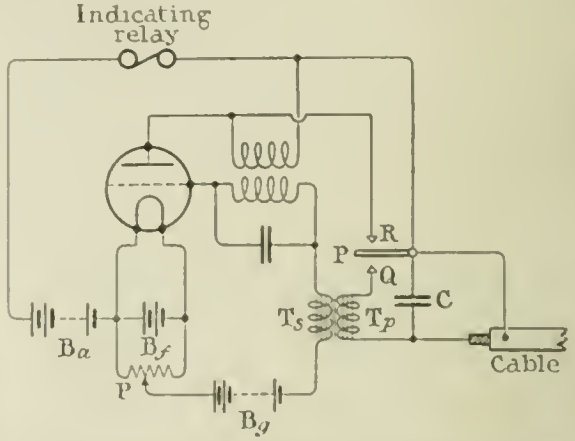

Fig. 13.—Circuits of Valve Relay for quasi-steady currents.

the relaying of slowly changing currents such as those from telegraph cables, the current and not its rate of change must be made to affect the relay. This is easily accomplished, with striking sensitivity, by placing an inductance of suitably large time-constant in the circuit, accumulating energy therein as long as the conditions permit, and then causing the current to change rapidly, as by breaking the circuit of the inductance, thus producing momentarily a large potential difference across the inductance. This momentary potential difference is applied directly, or through a step-up transformer, to the grid of the Valve Relay. Thus in Fig. 13 the incoming current from a cable charges condenser C. The switch tongue P of the automatic switch P Q R alternately dwells on contacts Q and R. During the Q contact a current from the cable and condenser C grows in T_p, storing in the transformer energy $\frac{1}{2} L i^2$. When P leaves Q this current rapidly falls to nothing, producing a change of grid potential $M (di/dt)$, where M is the mutual inductance between T_p and T_s, and (di/dt) is the greatest rate of fall of current in T_p. This trips the relay, which

* C.W. is an abbreviation for Continuous Wave.

is subsequently quenched by contact between P and R or by other means.

By arranging that the greatest rate of rise of current in T_p during "make" is considerably less than the greatest rate of fall during "break," and by preventing much or any reversal of current while the energy $\frac{1}{2} L i^2$ is being dissipated, the sensitivities to positive and negative currents may be made very unequal, and two such relays may be associated for double-current working.

In a trial with a certain transformer T_p T_s (Fig. 13), it was found possible to trip the relay reliably by breaking 4 microamperes in a primary of about 1 henry. The energy $\frac{1}{2} L i^2$ available for tripping the relay was thus 8×10^{-12} watt-seconds. Experiments on tripping a Post Office standard polarized relay in a similar manner

7. The Sensitivity and Selectivity of the Tuned High-frequency Valve Relay.

The superiority in the matter of sensitivity and selectivity of the tuned arrangement, referred to in Sections 4 and 5, is readily analysed. It is well known, and is implied in what has been said in Section 2, that a chief effect of reaction between the grid and anode circuits of a triode is to reduce the resistance of the system. Thus in Fig. 3, owing to the mutual inductance M between the two coils, the oscillatory resistance is reduced from R_1 to

$$R_1 - \frac{M g}{C_1}.$$

Since the setting of the relay consists precisely in increasing g as far as considerations of constancy and

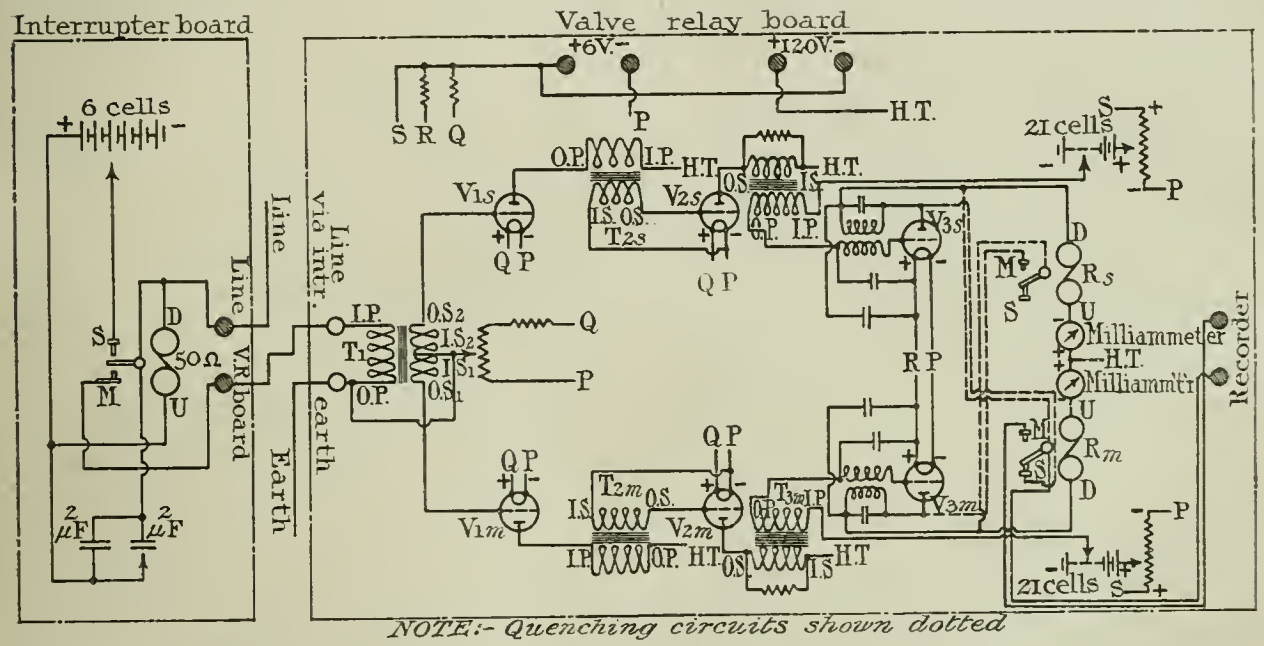

Fig. 14.—A Valve Relay bench set for double-current Morse. (With two preliminary amplifications.)

show that for this relay a corresponding energy of at least 5×10^{-5} watt-seconds (1 milliampere in over 100 henries) is necessary, i.e. over a million times as much for the Valve Relay.

The Valve Relay in this form must, it is thought, be adaptable to submarine cable working; but this is not an easy problem and only preliminary trials have so far been made. Fig. 14 shows the connections of a bench set for double-current working. There are two chains of three valves, responding respectively to positive and negative line currents, each chain comprising two amplifying valves between line and the Valve Relay proper. The interquenching system subsequently described in Section 8 is embodied. In a laboratory test this set recorded on a Wheatstone receiver at 45 words per minute with a sending electromotive force of only $\pm 1/200$ volt, and a key-down current of 1 microampere.

rapid quenching will allow towards the critical value at which the second term in this expression becomes equal to the first, the net resistance is very small indeed. In practice, when using a triode as in Fig. 6, it is found feasible to work with a margin of about 0·05 volt. If the threshold is at $-5{\cdot}5$ volts, examination of the curves shows that the slope falls by about 2 per cent on passing from the threshold to a potential 0·05 volt below. That is to say, the log. dec. δ_2 of the oscillatory circuit is reduced by the reaction to about 2 per cent of its inherent value. The sensitivity to accurately syntonized continuous-wave signals of the tuned arrangement is thus 50 times greater than that of the aperiodic arrangement of Fig. 9.

The selectivity as between continuous wave and spark is accounted for as follows. A signal consisting of a damped harmonic wave-train of decrement δ_1 in syntony with the relay circuit builds up in this circuit

an oscillation of which the maximum amplitude attained is proportional to the initial amplitude of the driving electromotive force of the incoming signal, and to the decrements function

$$\frac{1}{c_2}\left(\frac{c_1}{c_2}\right)^{\frac{c_1}{c_2}}.$$

Since by the action of setting the grid potential of the Valve Relay c_2 is made very small, as we pass from the relatively very large c_1 of a spark signal to the zero c_1 of a continuous-wave signal, this sensitivity factor changes approximately from

$$\frac{1}{c_2}\left(\frac{c_1}{c_2}\right)^{\frac{c_1}{c_2}} \quad \text{to} \quad \frac{1}{c_1}.$$

That is, for equal peak values of signal electromotive force in the receiving antenna, the peak potential rise on the grid from a continuous wave signal is $c_1 \div c_2$ times what it is from a spark signal. In practice this ratio $c_1 \div c_2$ might assume some such value as $0{\cdot}06 \div (2$ per cent of $0{\cdot}000) = 500$.

This factor 500 in favour of continuous wave is of course offset by the larger peak amplitude of the spark signal. For equal mean powers radiated, it is easy to calculate the ratio between spark peak amplitude and continuous-wave amplitude for any particular case.† Thus if the wave-length is 3,000 metres, the spark decrement $c_1 = 0{\cdot}06$, and the spark frequency 600, the spark amplitude is 10 times the continuous-wave amplitude. We are thus left with the figure $500 \div 10 = 50$, as giving the preference of the Valve Relay for continuous wave over spark signals of equal power.

8. General Limitations on Sensitivity and Speed of Working.

Since the incoming signal is applied to a grid which is at a potential considerably below that of the negative end of the filament and which consequently offers infinite resistance to the flow of current, the Valve Relay, unlike every form of mechanical relay, requires in theory no expenditure of energy to make it trip. The operative change of grid potential involves no doing of work on the grid corresponding to the useful work (as distinguished from the heating of the coils) which must be performed by the signal in an ordinary telegraph relay.‡ But just as it is in practice impossible to reduce indefinitely the resistance of the windings of an electromagnet and maintain magnetization without expenditure of power, so it is impossible to build wattless transformers or oscillatory circuits to produce the magnified wattless electromotive force applied to the grid of the Valve Relay. The sensitivity depends finally on the degree of perfection which it is practicable or convenient or economical to reach in the construction of such would-be wattless circuits. For example, in the Valve Relay shown in Fig. 7, the signal transformer has a secondary winding of 10,000 turns of S.W.G. 47 S.S.C. copper wire. The self-capacity of this winding at acoustic frequencies is in the neighbourhood of 50 micro-microfarads, and thus shunts the grid by a path of relatively very small impedance. If we could wind a secondary of larger inductance and smaller self-capacity, for example by using much finer wire, we should increase the sensitivity of the instrument.

The sensitivity is also inversely proportional to the margin to which the Valve Relay is adjusted. If the triode and its batteries were so constant that we could safely set the grid potential only 0·005 volt below the threshold instead of the more practical amount 0·05 volt, the strength of the limitingly weak operative signal would be divided by 10.

There is, however, a more appreciable effect than inconstancy forbidding the indefinite reduction of the margin. When the relay has been tripped and the oscillation started, it has to be reset by quenching the oscillation and allowing the currents in the anode and grid circuits to die down to their non-oscillatory values (small and zero respectively). This is, of course, an asymptotic process never fully completed; and if the rate of fall of current is still appreciable when the quenching contact is re-opened, there is an extra potential on anode or grid or both tending to re-ignite the oscillation. The longer the duration of quenching contact, the smaller the re-igniting potentials will be; but, whatever they are, they must be provided for by a margin sufficiently wide to make them inadequate to trip the relay afresh.

In contemplating the possibilities of the Valve Relay for high-speed telegraph work, we are faced therefore, as in all other relays, with a compromise between augmented speed and reduced sensitivity; but with this difference, that as the speed is increased there comes a time when the other relays fail to "mark," whereas here the relay would mark but would fail to "space" between the signals. For high-speed work, the acoustic Valve Relay of Fig. 7 is, as it stands, unsuitable. The tongue of the mechanical relay must quench at least several times during a Morse dot, and in this instrument its speed is insufficient for signalling at more than about 20 words per minute. The slowness is due to the fact that during oscillation a considerable mean grid current (about 0·2 milliampere) is built up in the secondary of the signal transformer which is of large inductance (some 50 henries). By using a triode with coarser grid and higher anode potential, this grid current can, however, be wholly suppressed. In the high-frequency form of relay (Section 5), grid current is harmless, since there is no large inductance in the grid circuit. The anode current in the magnets of the mechanical relay is then the limiting factor. The wireless Valve Relay of Fig. 10 is satisfactory up to 40 or 50 words per minute. For higher speeds it is preferable to provide for weaker oscillation and use an externally operated quenching switch, the mechanical relay being retained as an indicator only. The mechanical relay has then to move over only once per Morse dot, instead of several times per dot.

† Zenneck, "Lehrbuch der drahtlosen Telegraphie," 2nd Ed., p. 104. The calculation applies to the case of [illegible] by the oscillation

$$\int_0^\infty a_1 e^{-n_1 t} \, dt = a \frac{1}{N}$$

where n_1 is the frequency of the oscillation, and N is the spark frequency [illegible]

‡ The ordinary gas-engine governor corresponds to the potential of the grid of a valve relay; it does not perform the most perfect reversible thermodynamic operation in the sense of the word in dealing with the energy which it controls.

In the endeavour to reach really high speeds such as several hundred words per minute, the limit must ultimately be fixed by inability to quench fast enough. At 100 words per minute, with 5 quenches per Morse dot, the duration of quenching contact must be less than 1/400 second. An ingenious arrangement for double-current (or two-signal wireless) working, which avoids the necessity of quenching more than once per Morse dot, has been devised by Major Fuller, R.E., and Lieut. Lemon, R.E., of the Signals Experimental Establishment. The principle is shown in Fig. 12. M and S are the two Valve Relays, adapted to be tripped by the marking and spacing signals respectively. The tongues are shown in their positions of rest, the triodes not oscillating. At the beginning of a marking signal, the upper tongue moves to the left and stays there. At the beginning of the subsequent spacing signal, the lower tongue flicks over to the left, quenches M, whose tongue thereupon falls back to the right; this quenches S, thus restoring its tongue to the right; and all is still until another marking signal arrives.

9. Conclusion.

We have seen that the Valve Relay is an instrument of great sensitivity, yet requiring no delicate handling, adaptable for operation by signal currents of any form. With the multi-triode amplifiers developed during the last 3 or 4 years, it is feasible to work under commercial conditions with signals of much less power than is required to trip a Valve Relay; and it is, in fact, probable that this relay will frequently be employed at the end of a chain of amplifying triodes. It is not claimed, therefore, that the new relay is a receiver of unique sensitivity. In its low-frequency form, indeed, it is surpassed in sensitivity by the beautiful electro-mechanical instruments of Heurtley and Orling. But it is believed that no other relay capable of being manipulated by operators not highly skilled, and able to withstand ordinary conditions such as draught and vibration, can approach its performance.

Under laboratory conditions it is probable that the Valve Relay need never be indispensable, at least qua detector or relay; but situations are common enough where only the simple and robust instrument can give the service demanded, or where, for example, the mere battery consumption of a multi-triode amplifier would rule it out. A case in point is that of a wireless call device for the small islands and lighthouses lying a few miles off our coasts—an urgent problem to which a first solution was given by the author in 1915.* With the aid of the relay here described, a far better solution can now be provided.

In the foregoing pages, the function of the Valve Relay has been regarded as solely that of a relay. But it is a relay which responds when the signal reaches, if only for a brief moment, a certain strength, adjustable by the turning of a potentiometer handle, and expressible with precision as the difference between two voltmeter readings of the grid potential. It constitutes, therefore, a simple and convenient instrument for measuring peak values of potential or current, of any frequency and wave-form; and, in one such particular application, may prove an aid to precise wireless experimentation as a ready means of measuring signal strength.

My thanks are due to Lt.-Col. Cusins, C.M.G., R.E., Chief Experimental Officer of the Signals Experimental Establishment, for the facilities he has kindly afforded me in preparing this paper, and for permission to exhibit the several instruments, all of which have been produced at the Signals Experimental Establishment, Woolwich.

* Skerries Lighthouse, Cemlyn (Anglesey). See "Wireless Call Devices," *Institution of Post Office Electrical Engineers*, Paper No. 61.

Discussion at a Wireless Sectional Meeting of The Institution, 30 June, 1919.

Mr. A. A. C. Swinton: In my opinion the three-electrode valve tube constitutes one of the most wonderful discoveries in physics which has been made in modern times, and is the more interesting because it has eventuated out of research in pure science. It is not that the single tube itself gives such great amplification. Other forms of relay, for instance the Heurtley relay and the Orling relay, may be more sensitive, but if an attempt were made to put a number of these in series, great difficulties and complications would result, whereas with the three-electrode tube there is really no difficulty in connecting almost any number in cascade, thus getting the effect of the one multiplied by the other. I was recently told at the National Physical Laboratory that they had found with the particular tubes they were using each tube gave an amplification of 18 times. If we use six such tubes, that means an amplification of 18 to the power of 6, which is about 33 millions. A six-tube amplifier is quite a simple apparatus, whereas if we had six relays of other types in series we should find them very troublesome. One great point is this, that whereas with ordinary relays we get a great deal of distortion—even in a single relay—when we have a great many of them, one multiplying the result of the other, the distortion becomes so great that the arrangement becomes impracticable. In these thermionic tubes we are dealing with something which has practically no inertia and no momentum, and consequently in so far as the tube itself is concerned there is practically no distortion. I do not say we do not get some distortion in the instrument, because unfortunately it is usually necessary to use transformers between the tubes, but what distortion we do get is, I think, chiefly due to the transformers. As an instance of what can be done, take the wireless station at Paris which at a maximum is radiating perhaps 100 kw. If we assume that that 100 kw. is being radiated equally in all directions, then at a distance of 200 miles in the small space of, say, a square yard there is only something of the order of 0·15 microwatt available. The amount of energy is extremely small, and yet with one of these instruments, and using no large aerial, but only a receiving coil consisting of 20 or 30 turns one yard in diameter, we can get signals fully as loud as those we have just heard, and we can easily work recording instruments. It is really one of the most

marvellous triumphs of science in dealing with the almost infinitely small.

Mr. J. E. Taylor: The author makes a comparison between the energy required to trip an ordinary Post Office relay and this relay, which, I think, is not altogether appropriate. A more appropriate comparison would be the energy required to trip another form of wireless relay, which is also a trigger relay—I refer to the old-fashioned coherer receiver. I think it will be found that a great deal less energy is required to trip a coherer properly used than to trip a Post Office relay, although I have no doubt whatever that the energy required to trip the relay described in the paper is very much less than that required for the coherer. If the coherer receiver is used in the right way, and with not more than half a volt applied to the coherer, it is a much more reliable instrument than many of us imagine, although not robust in the sense that this relay is. It is subject to derangement by vibration and in many other ways which a valve relay is not. At the same time, I think the coherer still has some possible uses as a call device under certain special circumstances. Its main weakness was that it was affected very much by X's and stray signals. I should like to know whether the author's relay is immune to an appreciably greater extent.

Professor E. W. Marchant: I should like to say a few words first of all in regard to what Mr. Swinton has said. It has been one of my greatest difficulties during the past few years to emphasize the importance of technical research, as distinct from research in pure science. Mr. Swinton has pointed out how the scientific discovery of the unilateral conductivity of a vacuous space (in connection with which I should like to mention the name of Professor Fleming, as having done a great deal of pioneer work) has led to the wonderful developments which we have seen demonstrated this afternoon. The development of this relay is a great achievement and the three-electrode valve is a wonderful piece of apparatus, but it has involved a very large amount of *technical* research by highly trained technical men in order to bring it to its present condition. I should like, in an Institution such as this, to emphasize that point, because I think it is one which is extremely important and should be fully recognized; the importance of technical research in promoting the welfare of electrical engineering in this country cannot be over-emphasized. It is a subject which has been far too much overlooked in the past in the electrical engineering industry. I should like next to refer to the action of the valve as a physical phenomenon, that is, as a thing, the action of which is due to the discharge of electrons from a heated filament. A heated filament in a vacuum gives rise to a discharge of negative electrons. These negative electrons will move about freely in the space surrounding the filament, unless there is some controlling force acting on them to direct them. If one puts a plate above the filament or round it and connects that to the positive pole of a battery, the positive charge on the plate or cylinder will attract the electrons from the filament and cause a current to flow. If, on the other hand, the plate is negatively charged, the potential gradient is in the opposite direction and drives the electrons back again into the filament. Now, if one has, instead of a plate, a grid with holes in it, and one puts another plate above it, one gets the three-electrode valve. If one connects the plate to a high-potential battery, there is a big positive charge on the plate, and therefore a big positive charge tending to attract the negative electrons. If the grid were removed, of course there would be a current. If now the grid is charged so as to produce a positive potential gradient between the grid and the plate, there will be a potential gradient acting on the electrons when they emerge from the filament tending to move them towards the grid. Some of these electrons will come to the grid; the rest of them will shoot through the holes in the grid and come to the plate. If the holes in the grid are large as compared with the grid wires, there will be more electrons going through the holes than there are coming on to the grid wires. Therefore there will be a current amplification depending to a certain extent on the ratio between the size of the grid wires and the size of the holes. There is one interesting point about this. It will be noticed in the curve that the grid always has to be at a certain negative potential in order to prevent a current passing to the plate. We have to bring the grid to a negative potential, relatively to the filament, before the plate current is reduced to zero. The reason is this. If there is a high potential, say 400 or 500 volts, on the plate, it will produce a potential gradient between that and the filament, which will be, of course, in the right direction to produce a current. That current has to be stopped, and it is done by neutralizing the positive potential gradient due to the plate by a negative charge on the grid. This negative charge has to be adjusted to such a value as to make the potential gradient at the filament zero. It is the potential gradient at the point where the electrons are emitted that controls their flow. I should like to ask the author whether he has ever tried to use a condenser in the grid circuit instead of a potential divider in order to control the grid potential. If one has a leaky condenser connected between the grid and the negative terminal one can control the grid potential quite easily, and by altering the resistance of the leak one can vary the controlling potential, what the author calls the "threshold" voltage. In conclusion, I hope that, if new terms are to be introduced into wireless technology, some regard will be paid to their etymological meaning.

Professor C. L. Fortescue: In the very early days when the first reaction receivers were used, we learned, very much to our cost, that there was always a tendency to oscillate. It is a very old point, but it has remained for the author to make use of this feature. With regard to the application, I am unable to speak from the point of view of the land line and the cable telegraph, but from the wireless point of view it appears to me that there are perhaps two quite distinct possibilities which, although the author has mentioned them in the paper, he has hardly brought out quite clearly. We might divide those two, as he does, into the acoustic type and into receiving for wireless telegraphy direct. I take it that with the first of these

methods one would have some detector to give the acoustic frequency and that the rectified signals would then be passed on to the relay. That is using the device purely as a relay. There is the other application mentioned—that the author would use the instrument without a detector. I presume that he would have the telephones in series with the electro-mechanical relay. In my opinion it is as a relay with some other detector that this device is likely to have its future application. There would be one or two difficulties, if the device were to be used for direct reception without the other detector. For instance, it would appear that if one is receiving spark signals, instead of the note of the spark of the transmitting station being heard in the telephones, one would hear simply the note of the make-and-break of the small tongue of the electro-mechanical relay. It would be that particular note that would always appear in the telephones and consequently the great advantage which arises from an operator being able to read through interferences by means of a distinctive spark frequency would be lost. There would appear also to be the difficulty of atmospherics having the same note as the signals ; which would be a great disadvantage. Finally there is the point that the author does not claim that a signal of strength less than the Army R7 can be received directly. It may therefore be concluded quite definitely that it is as a relay or as a calling-up device that it would have its principal application. With regard to the difference in the reception of the spark and the continuous wave, on which the author has touched, I think that the theory is applicable to all forms of reaction receivers. There is really very little difference between this type of receiver and the ordinary reaction receiver. In either case one has the negative resistance in the valve. The only difference is that for this particular arrangement the negative resistance is an increasing resistance with increasing amplitude, and accordingly as the amplitude of the signal builds up in the receiver circuit the tendency to oscillate becomes more and more marked, the stage of instability is quickly reached, and the relay comes into operation. With the ordinary reaction detector, on the other hand, the tendency is to work the other way, viz. to arrange matters so that as the amplitude builds up the tendency to oscillate gets less and less ; in other words, to use the valve so that the negative resistance is decreasing with increasing amplitude. With regard to the reduction of the margin, has any method of quenching the oscillations other than that described in the paper been tried ? It would appear that this method of short-circuiting the coupling-coil might possibly lead to shock of the L C circuit and so to the restarting of the oscillation. If a resistance in parallel with the condenser could be used as a damping arrangement, it might be possible that the sudden rush of the anode current through the coupling coil could be avoided. Finally, there is a small point with regard to the design of the triodes. In the past the endeavour has been to produce valves having certain slopes of the characteristic curves. The valve designers and the valve manufacturers have found some difficulty in keeping these slopes within the prescribed limits. It would appear that the problem for them has now been somewhat widened. In future, apparently, they will have to control the rate of change of the slope. We have $d^2 i/dv^2$ now, as well as $d i/d v$. I do not know how manufacturers will like this added burden which has been thrown upon them.

Mr. B. Binyon : I was glad to hear Mr. Taylor compare the author's invention with a coherer. I am sure the author will not object to the comparison, because really the whole action of his instrument is analogous, though far superior to the coherer, except that his decohering arrangements are carried out by electrical rather than by mechanical means. There is one point which Professor Fortescue touched on and which may perhaps at first sight seem of minor importance, namely, the question of utilizing simultaneously, in conjunction with the valve relay, a telephone receiver. The author has pointed out that the principle of his high-frequency valve relay depends neither upon heterodyne nor upon rectification, and it appears to me impossible to operate a listening-in device simultaneously with the valve relay recorder. From a practical point of view this is of vital importance when utilizing such an arrangement in a station carrying out commercial traffic. It is essential if one man is working the recorder that somebody else should be listening-in independently, but on the same receiver circuits, to carry out any necessary tuning adjustments for wave fluctuations or weakening of couplings to eliminate disturbances. It should be borne in mind that if jamming occurs, or a local inductive effect trips the relay and disturbs the signals, there is no means of knowing the cause unless simultaneously listening-in be employed. From a traffic point of view it is very disadvantageous to have to switch over from the recorder to a telephone circuit in order to carry out adjustments, and this appears necessary unless such adjustments are done more or less at random and in the hope of getting the recording mechanism into working order again. The difficulty might be overcome by employing the audio-frequency relay operating, say, at the end of a multi-valve amplifier, in which case the high-frequency currents being rectified by the amplifier could operate simultaneously a telephone and recording circuit. The disadvantage of utilizing the audio-frequency relay in conjunction with a listening-in device is the loss of both sensitiveness and speed and all the advantages which the author has described in using a high-frequency type of relay. Alternatively, we could use an entirely independent receiver for simultaneous listening-in, but that, I think, would hardly meet the practical needs of the case, because some fault might develop in the valve relay receiver which might not occur in the independent receiver. It seems to me that the advantages of selectivity possessed by the relay which the author has described are to some extent lost owing to the necessity of switching over to a telephone receiver to adjust for the elimination of an interfering spark station. I cannot emphasize too strongly from the practical point of view my agreement with Professor Fortescue on the enormous advantages of aural reception, because it does keep the relative frequencies of whatever is coming in in the same proportion, and this applies.

As to the well-known method of high-speed recording by telephone I think that perhaps when seeing an extremely ingenious invention of this nature we are sometimes led astray and forget the perfection of the human ear in being able to distinguish and act as a selector in receiving wireless signals. Regarding high-speed recording, the theoretical fact that there is no expenditure of energy required to trip the relay, as has been pointed out in the paper, is at first sight very attractive, but at really high speeds the energy stored in the anode and grid inductances of the circuits must require an appreciable element of time to damp out. In the case of the high-frequency relay one would expect that the electrical quenching in the circuits would be quicker on the shorter wave-lengths than on the longer; however it is nearly always the longer wave-lengths which are employed for long-distance communication where high-speed recording is required. It would have been very interesting if the paper had given us some curves showing possible speed for a given signal strength plotted against wave-lengths, though it might be that the mechanical inertia of the parts at the higher speeds would obscure any difference in the speed possibilities on long and short waves. It would be interesting to have some idea of what part the quenching of the energy in the circuits plays at really high speeds, say of the order of 100 words per minute or above. Regarding the mechanical inertia of the relay itself, the author has mentioned the use of a mechanical quencher—I presume something in the nature of a rotary commutator quenching continuously rather like the old decoherer tapped continuously on the coherer. I should have thought that the speed of the relay would have been very much improved by the employment of such an independent mechanical quencher. I fail to see that the ingenious arrangement of Major Fuller's, illustrated in Fig. 12, has any advantages over the mechanical quencher; it offers no remedy for more rapid electrical quenching, and has the inherent disadvantage of the mechanical interaction of two spring-controlled relay tongues. Sensitivity is governed by the narrowness of the threshold which can be employed in practice. I think the author gives the adjustment as 0·05 volt. It seems to me that if the valve relay be employed as a calling device and is left for long periods, critically adjusted to the best point on the threshold, the falling-off in potential of the filament or high-tension battery might cause the threshold to creep away from the sensitive point so that the incoming signal would fail to trip the relay and give the call. I believe the author has some very ingenious idea to overcome defects of this nature.

Mr. W. E. Twells: I should like to know whether the author has made any experiments on really high-speed working. I mean of the order of 200 words a minute. Probably no country in the world is so well served telegraphically and telephonically with main underground cables as is the United Kingdom. The first cables introduced were telegraph cables pure and simple; later cables were reserved for telephone circuits. Some years ago, when an officer of the Post Office introduced a method of balancing the capacity and resistance of pairs so that it became possible to work telegraphs and telephones in the same cable, but the telegraph pairs were separated, and I think the problem of the future—in fact, it is the problem of the present—is to get telegraphs and telephones working indiscriminately either on a loaded pair or on an unloaded pair in the same cable. At present telegraphs are on unloaded pairs. Very considerable progress has already been made by the Post Office on these lines, and I think the difficulty will, as a matter of fact, be solved in the very near future. The speeds attainable are in the nature of 200 words a minute, and I should like to know whether the author's relay will work at anything approaching that. The problem, of course, is not a simple one; the relay must not be so sensitive that it responds to currents picked up from the telephone circuits, and it must be capable of ultimately working on single wires without interference with telephone circuits in the same cable. At the present moment there are circuits over 300 miles in length working on a pair of wires and, as each wire of a pair represents 30 tons of copper, there would be a very considerable saving if the telegraph currents were so small that they did not interfere with the working of the other wire of the pair but yet were able to work at the required speed.

Mr. A. B. Hart: The perfection of the thermionic valve or the triode has made possible the development of a practical telephone repeater for use in the telephone trunk lines of the country. The introduction of the telephone repeater has also revolutionized the design of long-distance lines; and whereas telephone engineers used to specify conductors weighing 400 lb. per mile, or even in some cases 600 lb. and 800 lb., they are now able to specify conductors of not more than one-tenth that weight of copper. But a telephone trunk-line system designed to use those small conductors in conjunction with telephone repeaters has its own peculiar troubles and difficulties, and the particular problem I have in mind at the moment is that of signalling through long lengths of small conductors. We used to be able to say that we could ring through anything we could speak through. Now we have got to a point where we have to say that we reach the signalling limit long before we reach the speaking limit. In fact, the indications show that in future there will be no limit to the distance over which speech is possible. In order to operate trunk lines economically it is necessary for the equipment to include apparatus for calling and clearing. These devices, as is probably well known, are generally in the form of relays shunted across the speaking circuit. These relays, of high impedance to current of speech frequency, are operated by the signalling current which is of the order of 10 milliamperes and of much lower frequency. In order to transmit currents of this magnitude through the high-resistance speaking circuits that telephone engineers now propose to use, it has been necessary to insert at intervals in these lines signalling repeaters which are designed on the lines of telegraph repeaters. Such signalling repeaters bring about some very undesirable complications in the maintenance of trunk lines, but in addition to that their very presence in these trunk lines introduces difficulties which interfere with the proper functioning

of the thermionic valve and its associated apparatus forming the telephone repeater. Wire telephone engineers have therefore been studying schemes to render unnecessary the use of separate ringing repeaters. The underlying principle of these schemes is the use of the triode, or thermionic valve as we still persist in calling it, for relaying signalling current as well as speech current. There is no time now, nor is this the proper occasion, to go into the details of the telephone repeater, but it will probably be sufficient for me to say that an essential element of that repeater must be a receiving apparatus that will respond to signalling currents of the same order of magnitude as the speech current, but the apparatus must not respond to speech-current frequency. It seems to me that the apparatus which the author has described at least offers one solution of that problem.

Mr. G. H. Nash : I desire to associate myself with Mr. Hart's contribution because it has covered the ground which I had intended to follow. There is one further adaption of this relay which the author might like to have suggested; it is that some ships of the Navy were fitted with wireless telephones and did not give very satisfactory service because of the difficulty of calling. It would seem possible by adapting this relay so that it be included in a selective circuit tuned to the calling frequency, to overcome thereby the calling trouble and supply a real need. There are two other matters to which I desire to refer. The first is to add a further contribution towards the discussion in praise of the valve. The second is to describe a difficulty which I have experienced in working with a certain type. Relating to the first, it may be of interest to review briefly the principal uses to which the valve has been put during the war. On the occasion of Major Fuller's recent paper, reference was made to the way in which the Germans first used this three-electrode valve to overhear conversations carried on by field telephones and telegraphs at the Front. Later, the British and French replied, using similar valves, and were able to overhear the German connections with, I believe, very much greater success than the Germans had had. The next development of note was the transmission of the spoken word from the Eiffel Tower to America in the early summer of 1915. Then followed a very large increase of valves used in wireless work, particularly in wireless telephony between aircraft and the ground. In 1917 it was introduced into the Navy in connection with submarine hunting, and now finally it has aided in multiplex working, so that there is to-day in operation a commercial circuit of over 100 miles in length carrying 10 simultaneous telegraph circuits and 4 telephone circuits. The telegraph circuits are capable of being operated in all the various ways which would be possible should each circuit have a wire itself. Finally, there is the extreme development in long-distance telephony due to the use of the three-electrode valve, or triode valve as the author prefers to call it, whereby it is only a question of expense which prevents us talking over the longest land distance, as for instance from Shanghai to London. This reference to the utility of the valve is not complete, but is sufficient to emphasize the epoch-making character of the apparatus. My second point relates to a difficulty I had in using the French type of valve on board ship because I could not get faithful articulation from it. The cause was finally traced to the use of the peculiar form of grid, which is a spiral wire in tension, and is to all intents and purposes a spiral spring. This is kept in vibration by external causes so that articulation is coloured by the frequency of the vibration. Further tests have been made with the valve in a stable place, but even then the valve was not satisfactory, because if a considerable amount of power was passed through the valve at the same frequency as the natural vibration of the grid, a slight discoloration occurred which rather suggested that the bombardment was capable of mechanically exciting the electrode. To overcome the trouble it was decided to use a triode with a very much stronger grid. The valve I have described is very largely used by the British Army, and I shall be glad to know whether the author has experienced a similar difficulty.

Major C. E. Prince : I think some previous speakers have not quite clearly distinguished between the ordinary method of amplification, and the author's special application of the valve, in which oscillation is started by the arrival of the signal. Such an effect, often produced temporarily or accidentally, has, in his device, been most neatly harnessed to practical ends. I should like to ask the author to give us some more information about the selectivity of the circuit. Obviously it is one of nearly zero decrement and can be absolutely in tune with the arriving wave, which does not have to be rectified, or combined with another frequency, as in heterodyne; so that the selectivity ought to be extremely high. Major Fuller, I believe, in his sound-ranging experiments, found this to be the case. It seems to me that one large field of usefulness for the trigger valve should lie in comparing or equalizing the strength of signals, a thing it is often very desirable to do. The trigger should afford an excellent means of accomplishing this, provided we realize that we are comparing only the peak voltages of the signals.

Mr. B. S. Gossling : The author has undoubtedly presented the valve makers with a new and definite problem. As Professor Fortescue has pointed out, valve designers will now have to take into account the curvature of the characteristic of the valve and not merely its slope. The curvature of the characteristic is commonly assumed to be the origin of the rectifying action of the valve, and has been very fully considered by many in that respect; but the author shows us the curvature of the characteristic applied to another purpose. It so happens that the portion of the characteristic which he works upon is one where the theory is at least comprehensible if not yet susceptible to exact treatment. That portion of the characteristic has a very exact geometrical form. It is in the form of an exponential curve, the constant of which has been very clearly shown in Professor Richardson's work on the distribution of the velocities with which electrons are emitted from the filament to be based solely on certain natural constants. It therefore appears extremely probable that the valves, as we have them now, give a curvature of very much the same order as

as ever likely to appear always provided that someone does not produce an ingenious method of eliminating the effect of the particular natural constants involved. Apart from that, the valve, as it stands, very conceivably represents something like high-water mark as regards curvature of the characteristic.

Mr. A. C. Brown: I should like to ask the author whether he has done anything in the way of using higher voltage currents, such as the current from electric light mains, and if so whether he has had any difficulty in the matter of cutting out the oscillations that are usually inherent in such electricity supply. That is a more important point than may appear at first sight, because, after all, the great difficulty in the permanent working of these lamps seems to be the detail of keeping accumulators fully charged, and therefore if the current to keep the filament hot can be derived from the electricity supply mains it would for many practical purposes be very useful.

Mr. J. Coxon: Some time before the war the author read a paper before the Institution of Post Office Engineers upon "Wireless Call Devices," and I believe he spent a good deal of time in trying to develop a satisfactory device. I think his perseverence deserves compliment, and credit is due to him for the development of the apparently highly satisfactory arrangement shown to us this evening. Credit would also seem due to those officers controlling the Experimental Signal Establishment for their foresight in granting facilities for work of such a nature. Perhaps the author, in replying, can quote the relative magnification of his valve and relay device, as compared with amplification by a series of valves only.

Captain L. B. Turner (*in reply, communicated*): Mr. Swinton's enthusiasm for the modern triode must be shared by all those who have worked with it; even more perhaps by those who have had the opportunity only of reflecting on its theory than by those who have also handled it in the laboratory and experienced its practical limitations. For the possibilities it opens up are indeed overwhelming. But Mr. Swinton has, I think, parted from practical possibilities in his computation of what may be achieved by multi-triode amplifiers as an alternative to the valve relay. An amplification of electromotive force of 18 in a single triode is not out of the way. Amplifications of 6 are got from the triode described in the paper, and 60 from another ordinary pattern containing a fine-mesh grid (the Marconi Company's "Q" valve). But the ratio of 18 per triode cannot in practice be maintained in an amplifier with many triodes in cascade; and Mr. Swinton's figure of 18^6 or 33 millions with the six-triode amplifier mentioned by him as used to amplify the signals, estimated at 0·06 microwatt, from the Lafel Tower would not be realized. This is fortunate for the operator to whose telephone would be delivered a power of 0·06 microwatt multiplied by the square of 33 millions, viz. 65,000 kw! As stated in Section 3, the single-triode valve relay exhibited will respond to a power of about 0·01 microwatt.

The comparison between the valve relay and a coherer (referred to by Mr. Taylor and Major Binyon) is interesting and apposite. There is an important distinction to be drawn, however, in that whereas the valve relay is a true potential-operated device absorbing no energy from the oscillatory circuit wherein the tripping potential is produced, the coherer does damp the circuit to which it is connected. Apart from this, however, and disregarding the inconstancy and manipulative difficulties of the coherer, the comparison suggested by Mr. Taylor would be that, whereas the valve relay requires, say, 0·1 volt to trip it, the coherer requires—I am told—some 5 or 10 volts, giving an energy ratio of at least over 2,000 in favour of the valve relay.

Professor Marchant asks whether a variable resistance in series with the grid has been tried for controlling its potential. The leaky grid condenser tending to maintain the grid at a slightly positive potential is an admirable rectifying device; but when the grid is negative, its own resistance is infinite and the leak would have no effect. In any case, however, a sliding potentiometer of tens or hundreds of ohms would remain preferable to a variable resistance of some such value as a megohm. Various other methods of controlling the approach to oscillation may be used, but for most purposes the grid potentiometer serves perfectly.

The point raised by Professor Fortescue, as to the possible re-igniting effect of the shock to the oscillatory system when the quenching short-circuit is removed, is an interesting one which had not occurred to me; but it must be remembered that the anode resistance is very large before the tripping signal arrives. At any rate, the effect appears to be a very small one which has not so far proved troublesome in practice, being swamped no doubt by the other re-igniting electromotive forces, and well covered by the margin which they, and the slight inconstancy of the triode, demand. I have found, on the other hand, that quenching by severing the anode or grid circuit is not satisfactory, as re-ignition is effected by the overshoot of potential at re-make.

Major Binyon raises a number of points requiring some comment. He mentions the desirability of an auditive watch over any relay apparatus actuated by wireless signals. I admit this; though I do not regard the continual tuning and coupling adjustments, which he appears to contemplate, as permissible, in a high-speed point-to-point station even to-day—certainly not five years hence. I agree that it would be no solution to attach telephones to the valve relay itself. But I think that a simple heterodyne receiver, to be used for supervision purposes simultaneously with the valve relay, coupled to the antenna or to whatever circuit immediately precedes the combination of Fig. 10 or its substitute, would meet the case. In wireless telegraphy as ordinarily practised to-day, the discriminating powers of the ear and brain are undoubtedly an enormous asset; but when we wish to work at high speed this faculty must be more or less wholly abandoned. The selective properties of the valve relay in the syntonized form have been described. With the introduction of a suitable limiter between it and the antenna, preventing an atmospheric from making up in violence what it lacks in frequency or lowness of decrement, a solution will, I think, be provided in the near future;

and a high-speed system will be produced freer from jamming than the low-speed aural reception of to-day. Major Binyon's remarks on the loss of sensitive adjustment of the valve relay when left long periods unattended, owing to drop in battery potentials, are specially significant in that the relay is in other respects particularly suitable for such unattended conditions. These changes can be fully provided for. The most sensible is likely to be the gradual drop of potential difference of the filament battery. This is easily compensated by arranging that the fall of filament current in a series resistance shall introduce a compensating rise of grid potential, by a method analogous to that described in the author's paper on "Wireless Call Devices"* for maintaining constant the anode current of a Fleming valve. Change of potential of the anode battery can be made to produce the necessary slight compensating change of grid potential by causing a current from the battery to warm, and thus control the resistance of, part of the grid potentiometer circuit. Temperature changes of battery electromotive force can, if necessary, be compensated in like manner. I do not think these refinements will often be wanted. Where the relay is to be left unattended, for periods which might extend to days or even weeks, another method which has been devised will probably be preferable. According to this, a local clock switches the relay off its normal duty for a minute or so at intervals of an hour or so; the grid potential is automatically raised until the relay trips, and in so doing lowers the potential by a suitable step and switches back to normal duty for another period.

Mr. Twells raises the question of the use of sensitive relays for high-speed underground cable telegraphy with such small currents as will not interfere with telephony through the same cables. This is an interesting development which seems to promise large economies. Experiments now in progress at the Signals Experimental Establishment with wireless signals indicate that the valve relay can be used at speeds such as 200 words per minute; but though this instrument could certainly be used, I am doubtful whether it is the simplest for the purpose described.

A somewhat similar application is discussed by Mr. Hart, who calls for a sensitive relay capable of performing the ringing and switching duties in a telephone circuit with currents of the same order of magnitude as the speaking currents. Here, I think, a form of valve relay would be very suitable. It might be of the type of Fig. 8, but designed so that the signal circuit tunes to, say, 50 periods per second instead of being sensibly aperiodic; or it might be of the type of Fig. 11, but with circuits tuned to, say, 50 periods per second instead of the wireless frequency.

It has been stated that the discrimination between spark and continuous-wave signals observed with the valve relay of Fig. 11 is very striking, and the quantitative theory is sketched in Section 7. Major Prince, in asking for further information as to selectivity, is probably referring to selection between two continuous-wave wave-lengths. Freedom from jamming from continuous-wave signals is, of course, more marked than by spark signals or atmospherics. It is easily calculated from the Bjerknes equation connecting decrement δ (in this case the decrement of the valve relay circuit alone), the tuned and slightly distuned wave-lengths λ_0 and λ, and the corresponding oscillatory currents (or potentials of grid of valve relay) i_0 and i:

$$\sqrt{\frac{i_0^2}{i^2}-1}=\frac{\pi}{\delta}\left(1-\frac{\lambda_0^2}{\lambda^2}\right)$$

Writing r as the ratio of tuned and distuned currents on passing from the tuned wave-length by x per cent of its value, this may be written

$$\sqrt{r^2-1}=\frac{2\pi x}{100\,\delta}$$

$$\therefore\ r=\sqrt{1+\frac{4\pi^2x^2}{10^4\delta^2}}$$

If we take the inherent (non-reactive) decrement of the oscillatory circuit of the valve relay as no lower than 0·01, we have in our supposed case $\delta=2$ per cent of $0{\cdot}01=0{\cdot}0002$. Hence when, for example, $x=0{\cdot}1$, $r=32$. That is, a distuning of one-tenth of 1 per cent in wave-length would divide the tripping potential on the grid by 32. It is to be noted that with valve relay reception we are affected by one wave-length only, and are not concerned with the two ranges of wave-length, of troublesome width in long-wave work, over which the beat note is audible in heterodyne reception.

* *The Institution of Post Office Electrical Engineers* Professional Paper No. 61, 15 February, 1915.

MAGNETOMOTIVE FORCE CALCULATIONS FOR CYLINDRICAL-FIELD ALTERNATORS UNDER STEADY SHORT-CIRCUIT CONDITIONS.*

By A. E. Clayton, B.Sc. (Eng.), Associate Member.

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Introduction.

The present paper is the outcome of an investigation into the leakage reactance of cylindrical-field alternators carried out by the author during the summer of 1915,† during which the need for exact methods in calculating the effect of armature reaction with such machines was made very apparent.

The paper, too, is in natural sequence to the work already published by the author on the operation of alternators under steady short-circuit conditions.

The general problem of armature reaction is dealt with in such textbooks as those by Arnold and Russell, and the methods followed in this paper are, to a certain extent, on the same lines as those employed by those writers, and, more recently, by Dr. S. P. Smith.‡ In addition, a very valuable mathematical treatment of the magnetomotive force of armature windings has been published recently by B. Hague.§

In the present paper, however, an attempt is made to apply a strict examination into the accuracy of the various methods in use for calculating the values of the various magnetomotive forces concerned in the action of cylindrical-field alternators under steady short-circuit conditions. Further, it is shown that M.M.F. calculations of cylindrical-field alternators, under such conditions, can be carried out very simply in terms of the actual maximum ampere-turns per pole on the exciting winding, and are, in fact, simpler and more exact than similar calculations with salient-pole machines.

1. The Operation of Cylindrical-field Alternators under Steady Short-circuit Conditions.

One of the most important works tests carried out on alternating-current generators is the "short-circuit," or "impedance" test. The chief object of this test is to determine the value of the reactance of the armature winding, as distinct from the reaction of the armature magnetomotive force.

The method commonly employed to effect this separation is based upon the fact that, on short-circuit, the difference between the main and armature magnetomotive forces gives rise to a magnetic flux, just sufficient to generate an electromotive force equal in value to the impedance voltage-drop in the armature winding. Thus, in Fig. 1, which shows the open and short-circuit characteristics of an alternator,

O A gives the value of the main M.M.F. on short-circuit;

A B the value of the armature M.M.F. on short-circuit; and

O B the unbalanced M.M.F. on short-circuit.

This unbalanced magnetomotive force serves to induce an electromotive force B C in the armature winding, and the impedance of the winding is obtained by dividing the value of this electromotive force by the value of the short-circuit current, A D.

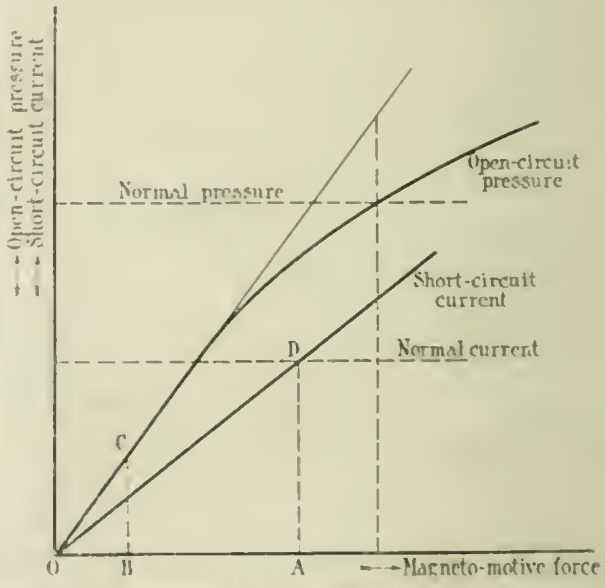

Fig. 1.—Open-circuit and short-circuit characteristics of an alternator, and the method of deducing the value of the reactance.

In a previous paper,¶ the author has shown that, on short-circuit, the armature M.M.F. closely approaches in value the main M.M.F., for cylindrical field machines. As a result, in order to obtain their difference with any degree of accuracy, it is absolutely essential to be able to calculate the values of these two M.M.F.'s with great exactitude. The difficulty of obtaining reliable figures for the reactance of high-speed alternators from the measured character-

* The Papers Committee invite written communications (with a view to publication in the *Journal*) if approved by the Committee, on papers published in the *Journal* within four months of the date on which they were first read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they refer.

† This paper was almost completed in 1915, but publication has been delayed, owing to the author having undertaken military duties early in 1916.

‡ S. P. Smith: "Notes on the Design of Electromagnetic Machines," *Electrician*, vol. 76, p. 777.

§ B. Hague: "The Mathematical Treatment of the Magnetomotive Force of Armature Windings," *Journal I.E.E.*, no. 7, vol. 55, p. 483.

¶ A. E. Clayton: "The Wave Shapes obtaining with Alternating current Generators under Steady Short-circuit Conditions," *Journal I.E.E.*, no. 46, vol. 54, p. 84.

istics on no-load, and short-circuit, is well appreciated by designers, and was brought forward quite recently by Mr. A. B. Field during the discussion of his paper* on "Some Difficulties in the Design of High-speed Generators."

Now the short-circuit test on an alternator is such that experimental errors should be, if anything, smaller, rather than greater, than for other tests. The characteristic is a straight line, and the value of the current in the armature winding is absolutely uninfluenced by even an abnormal variation in speed. It would appear, then, that the chief reason for the unreliable results obtained on deducing the value of the reactance from the measured characteristics, is to be found in the employment of insufficiently exact methods for the calculation of the various magnetomotive forces concerned.

With cylindrical-field machines, the distribution of the exciting winding introduces a certain degree of difficulty in the correct estimation of the effective values of the magnetomotive forces of the armature and field windings. Various methods are in use, some of them having a logical basis and others being admittedly empirical. All of these methods are, without doubt, sufficiently accurate for ordinary purposes such as the calculation of the full-load excitation. Few of them, however, are exact enough to permit of an accurate value of the reactance being deduced from the magnetization and impedance tests. The curves in Fig. 2 show the manner in which the ratio of the armature M.M.F. to the main M.M.F. on short-circuit depends upon the reactance of the winding, for various† normal M.M.F. ratios.

From these curves it will be seen that, in the case of a machine having a normal M.M.F. ratio of unity, an error of 2 per cent in the estimated value of the armature M.M.F. may give rise to an error of 20 or 30 per cent in the deduced value of the reactance. The great importance now attached to the value of the internal reactance of large high-speed alternators renders it very desirable that a reliable value of this reactance can be obtained experimentally. Hence it is very desirable that an exact method of calculating the value of the equivalent armature M.M.F. shall be available, and that the only errors possible in the deduced value of the reactance shall be such experimental errors as are unavoidable.

In a previous paper (referred to above) the author has published the results of oscillograph tests on alternating-current generators working under steady short-circuit conditions. These experiments show that the electromotive force induced in each of the armature conductors under such conditions contains very pronounced higher harmonics; but they also show that the actual current circulating in the short-circuited windings does not depart appreciably from the sinusoidal form, in the case of modern machines with cylindrical-field systems. (In the case of single-phase alternators it is assumed that efficient *amortisseurs* are provided.) The reasons for the elimination of the higher harmonics in the current wave are discussed in the previous paper and need not be enlarged upon here. With polyphase machines, the amplitude of the most important of the higher harmonics in the current wave is not likely to be more than 2 or 3 per cent of that of the fundamental, and its effect upon the virtual value of the current, as indicated by the ammeter, is thus not more than $\sqrt{(100^2 + 3^2)} - 100$, per cent, i.e. not more than 0·045 per cent. As a result, the current obtained on short-circuit may, even in cases where great accuracy is required, be taken as sinusoidal, the effect of the higher harmonics being absolutely negligible. In consequence, all effects tending to establish higher harmonics can be entirely neglected, and only those tending to give rise to the fundamental harmonic of the current wave need be considered.

With cylindrical-field machines, uniformly slotted, the air-gap reluctance may be taken as being constant over the whole pole-pitch. On normal short-circuit there is a complete absence of magnetic saturation, so that the flux distribution and the M.M.F. distribution have the same wave shape, and it is permissible to deal separately with the effects of each of the harmonics in both the main and the armature M.M.F. distribution wave-forms. In this respect, cylindrical-field alternators permit of more exact calculations than salient-pole machines, in which the air-gap under the pole is not constant, and, in addition, the calculation of the exact effect of the pole fringe presents a certain degree of difficulty.

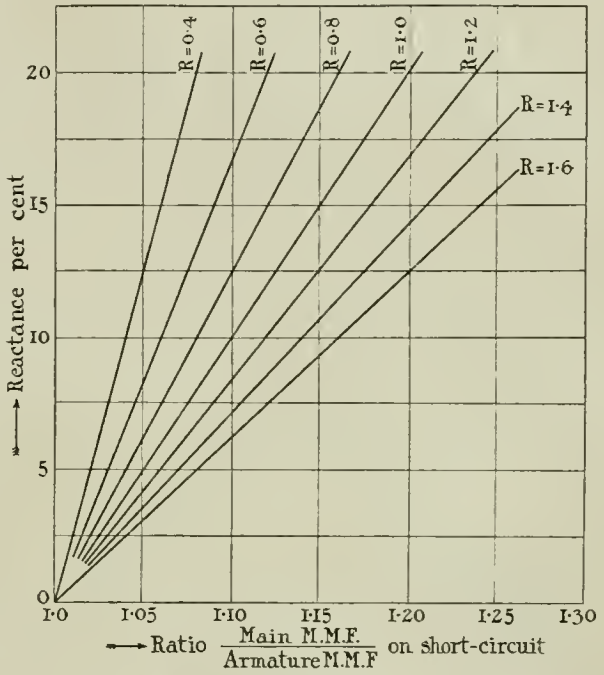

FIG. 2.—The influence of the value of the reactance upon the ratio (Main M.M.F.) : (Armature M.M.F.) on short-circuit, for various normal M.M.F. ratios (R).

Such a method of treatment, on the lines of that employed by Arnold in dealing with the general problem of armature reaction, although justified in the particular case under consideration, is not strictly accurate for normal conditions when the iron parts of the machine can no longer be regarded as being unsaturated.

* *Journal I.E.E.*, 1916, vol. 54, p. 83.

† That is, the ratio of the main M.M.F. on open circuit and normal voltage, to the armature M.M.F. on full load. The curves in Fig. 2 are based upon a straight-line magnetization curve.

II. The Main Magnetomotive Force.

The M.M.F. distribution of a concentrated, full-pitch winding is of the rectangular form shown in Fig. 3*a*. The Fourrier series representing this wave-form is:

$$a = \frac{4}{\pi} X \left\{ \sin\theta + \frac{1}{3}\sin 3\theta + \frac{1}{5}\sin 5\theta + \quad \right\} . \quad (1)$$

In this series, $X = N_c I_c$, the total excitation ampere-turns per pole; and a is the actual value of the magneto-

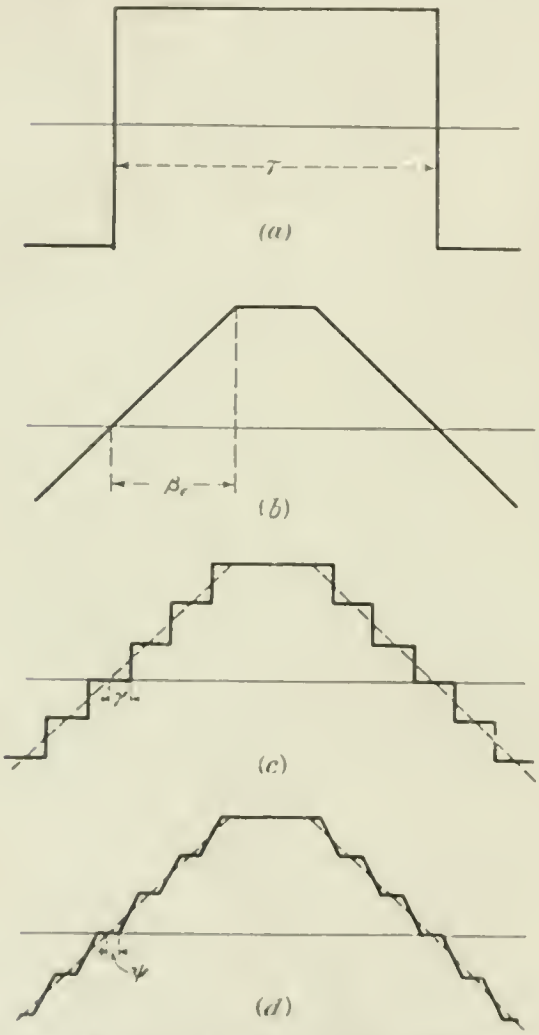

Fig. 3.—Magnetomotive force distribution wave-forms:

(*a*) Concentrated, full-pitch winding.
(*b*) Winding uniformly distributed over $2\beta_e$ radians per pole.
(*c*) Winding assumed concentrated at centres of slots.
(*d*) Actual M.M.F. distribution-form with cylindrical-field machine.

motive force at a point distant by θ electrical radians from the origin.

Such a winding therefore tends to establish magnetic fields of 1, 3, 5, 7, etc., times the normal number of poles, and of 1/1, 1/3, 1/5, 1/7 etc., times the amplitude of the main harmonic.

In actual practice the winding is not concentrated, but distributed over a considerable portion of the pole-pitch. If the winding were distributed perfectly uniformly over the wound portion of the field system, the M.M.F. distribution would be of the trapezium form shown in Fig. 3*b*, and represented by the Fourrier series:

$$a = \frac{4}{\pi} N_c I_c \cdot \frac{1}{\beta_e} \left\{ \sin\beta_e \sin\theta + \frac{1}{9}\sin 3\beta_e \sin 3\theta + \frac{1}{25}\sin 5\beta_e \sin 5\theta + \ldots \right\} (2)$$

In this series, β_e is one-half the spread of the winding, in electrical radians, per pole.

The reduction in the importance of the higher harmonics in the case of the distributed winding, compared with that of the concentrated winding, is made very apparent by considering the two series given above.

Surface windings being quite unsuited to modern conditions, the conductors are actually distributed in slots, and the trapezium wave no longer strictly represents the actual M.M.F. distribution.

As a first approximation, the M.M.F. due to the conductors in each slot may be considered to be concentrated at the centre line of the slot. The M.M.F. distribution will then be of the "stepped" form shown in Fig. 3*c*. This "stepped" form is obtained by combining the required number of rectangular waves, as in Fig. 3*a*, displaced respectively by an angle corresponding to one slot-pitch.

This wave, with rectangular steps, is represented by the series*:

$$a = \frac{4}{\pi} \cdot \frac{N_c I_c}{s_c} \left\{ (\sin\beta_e/\sin\gamma)\sin\theta + \frac{1}{3}(\sin 3\beta_e/\sin 3\gamma)\sin 3\theta + \ldots + \frac{1}{n}(\sin n\beta_e/\sin n\gamma)\sin n\theta + \ldots \right\} . \quad (3)$$

In this series, n is the order of the harmonic; γ is the angle indicated in Fig. 3*c*, and corresponding to one-half of a slot-pitch.

Thus $\gamma = \pi/Q_c \cdot \pi/2$

where Q_c is the number of slot-pitches per pole;
and s_c is the number of slots wound per pole.

The amplitudes of the various harmonics in this "stepped" wave are thus obtained by multiplying the amplitudes of the corresponding harmonics in the rectangular wave by the factor $\sin n\beta_e/(s_c \sin n\gamma)$.

In a similar manner, the amplitudes of the various harmonics in the "stepped" wave are obtained by multiplying the amplitudes of the corresponding harmonics in the trapezium wave-form by the factor $n\beta_e/(s_c \sin n\gamma)$.

Of these two factors, the former is the ordinary "distribution factor" in common use. The latter is also of interest, as it indicates the effect of placing the winding in slots upon the values of the higher harmonics, and thus affords an indication of the magnitude of the spacing ripple.

The magnetomotive force due to each slot group is not,

* The mathematical proof of this series is given in the Appendix.

however, concentrated at the centre line of the slot, but is distributed over the width of the slot. As a result, the actual M.M.F. distribution corresponds more closely to that of the uniformly distributed winding, the "steps" in the M.M.F. wave being no longer rectangular, but inclined, as in Fig. 3*d*.

The general case of a wave shape of this type is worked out in the Appendix. For all ordinary purposes, however, it is sufficient to take the M.M.F. wave illustrated, in which the M.M.F. due to each slot is distributed over one-half of the slot-pitch. For this latter M.M.F. wave the Fourrier series is:

$$x=\frac{4}{\pi}\cdot\frac{1}{\beta_e}\cdot N_e I_e\left\{(\sin\beta_e/\cos\psi)\sin\theta + \frac{1}{3^2}(\sin 3\beta_e/\cos 3\psi)\sin 3\theta + \frac{1}{5^2}(\sin 5\beta_e/\cos 5\psi)\sin 5\theta + \ldots\right\} \ldots (4)$$

In this series, ψ is the angle indicated in Fig. 3*d*, and corresponding to one-quarter of a slot-pitch. Thus

$$\psi = 1/Q_e \cdot \pi/4, = \gamma/2$$

The amplitudes of the various harmonics in the M.M.F. wave shown in Fig. 3*d* are obtained from those of the corresponding harmonics in the rectangular wave (Fig. 3*a*) by multiplying by the factor $\sin n\beta_e/(n\beta_e\cos n\psi)$.

Similarly, the amplitudes of the various harmonics in the actual wave shown in Fig. 3*d* are $1/\cos n\psi$ times the, amplitudes of the corresponding harmonics for a uniformly distributed winding.

Spacing ripple.—From the series given, (3) and (4) the amplitude of any particular harmonic in either of the two stepped M.M.F. waves can readily be obtained. It is, however, a convenience in practice to resolve the actual M.M.F. wave into:

(1) A trapezium distribution form, corresponding to the case of a perfectly distributed winding, having the same spread;

and (2) A spacing ripple, due to the winding being placed in slots.

The wave-forms of the two spacing ripples corresponding to the waves indicated in Figs. 3*c* and 3*d* are shown in Figs. 4*a* and 4*b* respectively.

The Fourrier series representing the spacing ripple is obtained, simply, from the difference between the series representing the actual M.M.F., and that representing the corresponding uniformly-distributed winding.

Case 1.—Ripple as in Fig. 4*a*. Harmonic analysis of spacing ripple:

$$x=\frac{4}{\pi}\cdot\frac{N_e I_e}{s_e}\left\{(\sin\beta_e/\sin\gamma)\cdot\sin\theta + \frac{1}{3}(\sin 3\beta_e/\sin 3\gamma)\sin 3\theta + \ldots\right\} - \frac{4}{\pi}\cdot\frac{N_e I_e}{\beta_e}\left\{\sin\beta_e\sin\theta + \frac{1}{9}\sin 3\beta_e\sin 3\theta + \ldots\right\}$$

$$= \frac{4}{\pi}\cdot N_e I_e\left\{\sin\beta_e\left(\frac{1}{s_e\sin\gamma}-\frac{1}{\beta_e}\right)\sin\theta + \frac{1}{3}\sin 3\beta_e\left(\frac{1}{s_e\sin 3\gamma}-\frac{1}{3\beta_e}\right)\sin 3\theta + \ldots\right\} \ldots (5)$$

The amplitude of the nth harmonic in the spacing ripple is thus:

$$\frac{4}{\pi}\cdot N_e I_e\left\{\frac{1}{n s_e\sin n\gamma}-\frac{1}{n^2\beta_e}\right\}\sin n\beta_e$$

The case of the fundamental harmonic, and that of those of the $(2Q_e+1)$th and the $(2Q_e-1)$th orders, are of particular interest. Expressed in terms of the amplitude

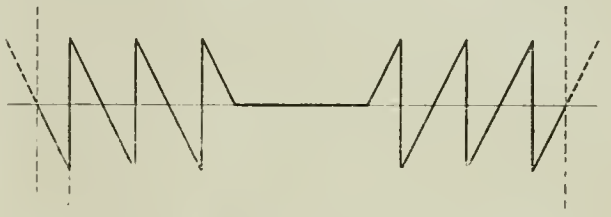

FIG. 4(*a*).—Spacing ripple corresponding to Fig. 3(*c*).

of the fundamental harmonic of the trapezium wave-form these harmonics in the spacing ripple have the following values:

Fundamental harmonic of spacing ripple

$$\left\{1/(s_e\sin\gamma)-1/\beta\right\}\cdot 100, \text{ per cent}$$

$(2Q_e+1)$th harmonic

$$\doteqdot -2(Q_e+1)/(2Q_e+1)^2\cdot 100, \text{ per cent}$$

$(2Q_e-1)$th harmonic

$$\doteqdot -2(Q_e-1)/(2Q_e-1)^2\cdot 100, \text{ per cent}$$

The total value of the amplitudes of the $(2Q_e+1)$th, and the $(2Q_e-1)$th, harmonics in the stepped M.M.F.

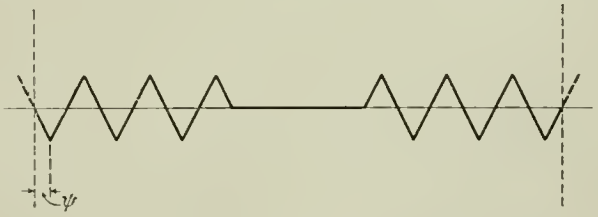

FIG. 4(*b*).—Spacing ripple corresponding to Fig. 3(*d*).

wave are thus $-1/(2Q_e+1)$, and $-1/(2Q_e-1)$, respectively, of the value of the fundamental harmonic.

The proofs of the above expressions are given in the Appendix.

Case 2.—Ripple as in Fig. 4*b*. Harmonic analysis of spacing ripple:

$$x=\frac{4}{\pi}\cdot\frac{1}{\beta_e}\cdot N_e I_e\left\{(\sin\beta_e/\cos\psi)\sin\theta + \frac{1}{9}(\sin 3\beta_e/\cos 3\psi)\sin 3\theta + \ldots\right\} - \frac{4}{\pi}\cdot\frac{1}{\beta_e}\cdot N_e I_e\left\{\sin\beta_e\sin\theta + \frac{1}{9}\sin 3\beta_e\sin 3\theta + \ldots\right\}$$

$$= \frac{4}{\pi}\cdot\frac{1}{\beta_e}\cdot N_e I_e\left\{(1/\cos\psi-1)\sin\beta_e\sin\theta + \frac{1}{9}(1/\cos 3\psi-1)\sin 3\beta_e\sin 3\theta + \ldots\right\} \ldots (6)$$

The amplitude of the nth harmonic in this spacing ripple is thus:

$$\frac{4}{\pi}\cdot\frac{1}{n^2\gamma_s}\cdot N_s I_s\left\{(1-\cos n\psi-1)\sin n\beta_s\right\}$$

In terms of the fundamental harmonic of the trapezium wave the values of the amplitudes of the following harmonics in the spacing ripple thus become:

Fundamental harmonic of spacing ripple

$$=(1-\cos\psi-1)\ 100,\ \text{per cent}$$

$$\doteq\frac{\psi^2}{2}\cdot 100,\ \text{per cent}$$

$$\doteq\frac{\pi^2}{32\,Q_s^2}\cdot 100,\ \text{per cent}$$

$$(2Q_s+1)\text{th harmonic}\doteq-\frac{(1-\psi-1)}{2Q_s+1}\cdot 100,\ \text{per cent}$$

where $\psi=1-Q_s\ \pi+1$

$$(2Q_s-1)\text{th harmonic}\doteq-\frac{(1-\psi-1)}{(2Q_s-1)^2}\cdot 100,\ \text{per cent}$$

The values of these particular harmonics in the spacing ripple thus reduce to very simple expressions.

The total value of the $(2Q_s+1)$th and the $(2Q_s-1)$th harmonics in the stepped wave shown in Fig. 3*d* are thus $-4Q_s\left\{\pi+2Q_s+1)^2\right\}$ and $-4Q_s\left\{\pi+2Q_s-1)^2\right\}$ respectively of the value of the fundamental harmonic.

The proofs of the above expressions are given in the Appendix.

It will be noticed that in no case of a normal machine can the spacing ripple contain harmonics of orders that are absent in the trapezium wave corresponding to the same spread. The effect of spacing the winding in slots is simply to modify the value of harmonics, which would be present if the winding were uniformly distributed over the same portion of the pole-pitch, and in certain cases to alter the sign of some of the harmonics. The sign of the harmonic is changed, in the case of the ripple in Fig. 4*a* when $\sin n\gamma$ is negative, and in the case of the ripple in Fig. 4*b* when $\cos n\psi$ is negative. This corresponds, in both cases, to all the harmonics from the $(2Q_s+1)$th to the $(4Q_s-1)$th inclusive.

The case of a rotor slotted so that $Q_s=15$, and $s_s=10$ and 12 respectively, has been worked out for both types of spacing ripples, and the results are given in Tables 1A and 1B. These Tables show clearly the relative importance of the various harmonics.

The fundamental harmonic of the spacing ripple is thus very small, in particular for the case of the ripple shown in Fig. 4*b*, which corresponds very closely to the conditions actually obtaining in practice. The amplitude varies inversely as the square of the number of slot pitches per pole, and the large values obtaining for this latter number result in the spacing ripple being well less than 0·2 per cent of the fundamental harmonic of the trapezium wave-form.

TABLE 1A.

Harmonic Analysis of the M.M.F. Wave-forms, as in Fig. 3e, for $Q_s=15$, and $s_s=10$ and 12, respectively.

Order of Harmonic	Amplitude of Harmonic					
	$s_s=10$			$s_s=12$		
	Trapezium Wave	Spacing Ripple	Total Stepped Wave	Trapezium Wave	Spacing Ripple	Total Stepped Wave
1	100·00	0·18	100·18	100·00	0·18	100·18
3	0	0	0	−6·86	−0·14	−7·00
5	−4·00	−0·19	−4·19	0	0	0
7	2·04	0·20	2·24	1·26	0·12	1·38
9	0	0	0	−1·24	−0·20	−1·44
11	−0·83	−0·21	−1·04	0·83	0·21	1·04
13	0·59	0·23	0·82	−0·36	−0·14	−0·50
15	0	0	0	0	0	0
17	−0·34	−0·29	−0·63	0·21	0·18	0·39
19	0·28	0·32	0·60	−0·28	−0·32	−0·60
21	0	0	0	0·23	0·(8)	0·62
23	−0·19	−0·49	−0·68	−0·11	−0·31	−0·42
25	0·16	0·68	0·84	0	0	0
27	0	0	0	0·09	0·68	0·77
29	−0·12	−3·33	−3·45	−0·12	−3·33	−3·45
31	0·10	−3·32	−3·22	0·10	−3·32	−3·22
33	0	0	0	−0·06	0·(9)	0·63
35	−0·(8)	0·68	0·60	0	0	0
37	0·07	−0·40	−0·33	0·05	−0·31	−0·26
39	0	0	0	−0·07	0·40	0·33

TABLE 1B.

Harmonic Analysis of the M.M.F. Wave-form, as in Fig. 3d, for $Q_s=15$, and $s_s=10$ and 12, respectively.

Order of Harmonic	Amplitude of Harmonic					
	$s_s=10$			$s_s=12$		
	Trapezium Wave	Spacing Ripple	Total Stepped Wave	Trapezium Wave	Spacing Ripple	Total Stepped Wave
1	100·00	0·14	100·14	100·00	0·14	100·14
3	0	0	0	−6·86	−0·84	−6·94
5	−4·00	−0·14	−4·14	0	0	0
7	2·04	0·15	2·19	1·26	0·09	1·35
9	0	0	0	−1·24	−0·15	−1·39
11	−0·83	−0·16	−0·98	0·83	0·16	0·98
13	0·59	0·17	0·76	−0·36	−0·10	−0·46
15	0	0	0	0	0	0
17	−0·34	−0·21	−0·55	0·21	0·13	0·34
19	0·28	0·23	0·51	−0·28	−0·23	−0·51
21	0	0	0	0·23	0·27	0·50
23	−0·19	−0·33	−0·52	−0·11	−0·21	−0·32
25	0·16	0·46	0·62	0	0	0
27	0	0	0	0·09	0·45	0·54
29	−0·12	−2·16	−2·28	−0·12	−2·16	−2·28
31	0·10	−2·10	−2·00	0·10	−2·10	−2·00
33	0	0	0	−0·06	0·42	0·36
35	−0·(8)	0·40	0·32	0	0	0
37	0·07	−0·28	−0·21	0·05	−0·17	−0·12
39	0	0	0	−0·07	0·21	0·14

Further, the spacing ripple in the armature M.M.F. will also contain a small, positive, fundamental harmonic. So that the error introduced by omitting entirely the fundamental harmonics of the spacing ripples of both the main and the armature magnetomotive forces will be quite negligible.

Hence, so far as the fundamental harmonic is concerned, the spacing ripple can be entirely neglected and the value of the fundamental harmonic of the trapezium wave may be taken as sufficiently accurate, even for purposes where great exactitude is required.

So far as the higher harmonics in the main M.M.F. distribution are concerned, although their magnitude is relatively small in terms of the fundamental, in the resulting M.M.F., due to the combined action of the main and armature magnetomotive forces, their importance is considerably enhanced. This is due to the fact that the chief effect of the reaction of the armature M.M.F. is to reduce the magnitude of the fundamental harmonic. This point is fully discussed in the previous paper * by the present author on the operation of alternators under steady short-circuit conditions.

As a result, the electromotive force induced in the individual armature conductors contains higher harmonics of very important magnitudes. Nevertheless, the spread of the armature winding causes a great reduction in the importance of the higher harmonics in the total electromotive force induced in the armature winding. Further, the great reactance of the winding to currents of high orders assists in reducing the higher harmonics in the current wave on short-circuit to an absolutely negligible amount. So that the current wave does not depart appreciably from a pure sine wave, and the higher harmonics do not influence the reading of the ammeter.

Hence, as the higher harmonics cannot conceivably influence the value of the fundamental harmonic, their effect can be entirely neglected in M.M.F. calculations for cylindrical-field alternators under steady short-circuit conditions.

As a result, in dealing with calculations of the main M.M.F. of a cylindrical-field alternator working under steady short-circuit conditions, the spacing ripple can be entirely neglected and the M.M.F. may be taken as being equivalent to one of sinusoidal distribution. The amplitude of this equivalent sinusoidal M.M.F. is, simply, the amplitude of the fundamental harmonic of the trapezium wave-form representing the case of a perfectly distributed winding, corresponding to the actual spread of the exciting winding.

Thus, the amplitude of the equivalent sinusoidal M.M.F. for the main exciting winding

$$= \frac{4}{\pi} \times \frac{\sin \beta_e}{\beta_e} N_e I_e$$

III. The Armature Magnetomotive Force.

The armature winding, as in the case of the main exciting winding, is distributed in slots over a fair proportion of the pole-pitch for each phase. As a result, the magnetomotive-force distribution wave-form of each phase has a spacing ripple, just as in the case of the field winding. No measurable error will, however, be introduced if this spacing ripple is entirely neglected and the winding is taken as being uniformly distributed. Moreover, the slight error introduced by neglecting the effect of the spacing ripple, in the case of the armature winding, would simply neutralize the equally slight error introduced by omitting the ripple in the case of the main exciting winding.

At first, attention is confined to the case of normal full-pitch windings, fractional pitch windings being dealt with later. It is further assumed that, in the case of single-phase machines, efficient amortisseurs of the squirrel-cage type are provided, and that, in the case of polyphase machines, the phases are balanced.

(1) *Single-phase machines.*—The resulting M.M.F. distribution for a single-phase armature winding is of exactly the same type of wave-form as for the main exciting winding, with cylindrical-field machines. The M.M.F., however, instead of being constant, alternates in step with the armature current. Now this armature current on short-circuit is almost a pure sine wave, and the relatively small higher harmonics present serve simply to influence the value of the higher harmonics in the electromotive forces induced in the various windings. Since all effects which do not influence the value of the fundamental harmonic of the current wave can be entirely neglected, it follows that the armature current may be taken to be a pure sine wave, and that the amplitude of the trapezium wave-form representing the armature M.M.F. may be taken to vary periodically according to a sine law. The series representing the M.M.F. distribution of the armature winding is therefore:

$$y = \frac{4}{\pi} \cdot \frac{N i}{\beta} \left\{ \sin \beta \sin \theta + \frac{1}{9} \sin 3\beta \sin 5\theta + \frac{1}{25} \sin 5\beta \sin 5\theta + \ldots \right\}$$

In this expression,

β = one-half the spread of the armature winding, in electrical radians, and is therefore equal to $(s/Q)\,\pi/2$;

i = the value of the armature current at any instant, as given by $i = I_{max.} \sin w t$, where $I_{max.}$ is the maximum value of the sinusoidal armature current, i.e. $I_{max.} = I\sqrt{2}$;

and y = the value of the armature M.M.F. at a point distant by θ electrical radians from the origin, at the instant when the current is equal to i.

The armature current thus tends to establish alternating magnetic fields of one, three, five, etc., times the normal number of poles, all of sinusoidal distribution and all alternating at normal frequency in step with the armature current.

According to a well-known theorem, each of these alternating magnetomotive forces can be exactly represented by two constant, rotating, components, each equal in magnitude to one-half of the maximum value of the alternating M.M.F. represented, and rotating at synchronous speed in opposite directions. These constant, rotating, components will be of sinusoidal distribution.

With the fundamental harmonic, the normally rotating component moves in step with the main exciting winding, and acts simply as a back magnetomotive force of sinusoidal distribution and of amplitude equal to

$$0{\cdot}5 \times \frac{4}{\pi} \cdot \frac{\sin \beta}{\beta} \cdot N I \sqrt{2}$$

* A. E. Clayton: "The Wave Shapes obtaining with Alternating-current Generators under Steady Short-circuit Conditions," *Journal I.E.E.*, 1916, vol. 54, p. 84.

The inverse rotating component moves backward relatively to the magnet system, at twice normal speed. It therefore induces currents of twice the normal frequency in the amortisseurs, which currents compensate exactly—with perfect damping—the action of the inverse component and prevent it from acting upon the main exciting winding, and from thence reacting upon the armature winding. This inverse rotating component therefore exercises no effect upon the value of the current circulating in the armature winding, and need not further be considered.

With the higher harmonics of the M.M.F. distribution, both the normal and inverse rotating components move backwards relatively to the magnet system, at speeds of $(1 \pm 1/n)$ of the speed of the rotor—the components of the third harmonic at 2/3 and 4/3 of normal speed, and so on. These magnetomotive forces corresponding to fields of n times the normal number of poles, electromotive forces, and currents of two, four, six, etc., times the normal frequency are set up in the amortisseurs, which currents thus completely compensate the action of the higher harmonics in the M.M.F. wave of the armature.

The higher harmonics in the M.M.F. distribution wave of the armature thus have no effect upon the value of the armature current on short-circuit, and therefore can be omitted in all calculations concerned therewith.

As a result, for a compensated single-phase cylindrical-field alternator working under steady short-circuit conditions, the effect of the armature reaction may be taken as equivalent to a steady sinusoidal M.M.F. of one-half the maximum value of the fundamental harmonic of the actual alternating M.M.F., and rotating in synchronism with the main exciting winding.

Thus, the amplitude of the equivalent sinusoidal M.M.F. for the armature winding, with single-phase machines

$$= 0{\cdot}5 \times \frac{4}{\pi} \cdot \frac{\sin\beta}{\beta} \cdot N\,I\,\sqrt{2}.$$

(2) *Two-phase machines.*—As with single-phase machines, each phase of the armature gives rise to an alternating M.M.F. of trapezium distribution-form and alternating in step with the current. The armature currents being sinusoidal, the M.M.F. distribution-forms of the two phases at any instant may be represented by the two series :

M.M.F. due to phase 1 :

$$y_1 = \frac{1}{\pi} \times \frac{N I \sqrt{2}}{\beta} \sin\omega t \left\{ \sin\beta \sin\theta - \frac{1}{9} \sin 3\beta \sin 3\theta - \ldots \right\}$$

where N is the number of turns per phase, per pole.

M.M.F. due to phase 2 :

$$y_2 = \frac{4}{\pi} \cdot \frac{N I \sqrt{2}}{\beta} \cos\omega t \left\{ \sin\beta \cos\theta + \frac{1}{9} \sin 3\beta \cos 3\theta + \ldots \right\}$$

where $\beta = \pi/4$.

The magnetomotive forces of the two phases are displaced by one-quarter of a period in time, and by one-quarter of the double pole pitch in space.

The resulting M.M.F. at any point distant θ from the origin O can be obtained by summing the above two series.

The resulting M.M.F. distribution for the joint action of the two phases can be obtained by considering separately the various harmonics and resolving each of them into its two rotating components.

In the case of the fundamental harmonics, the normal rotating components for the two phases are in exact conjunction, as shown in Fig. 5. On the other hand, the inverse rotating components are in exact opposition, so that the inverse component of the one phase is exactly neutralized by that of the other. As a result, so far as the fundamental harmonics are concerned, the joint effect of the two phases is to produce a synchronous rotating M.M.F. of sinusoidal distribution and in opposition to the main exciting M.M.F. The amplitude of this steady sinusoidal M.M.F. is $\frac{4}{\pi} \times \frac{\sin\beta}{\beta} N\,I\,\sqrt{2}$.

For the third harmonics, the displacement between the windings corresponds to $3\pi/2$ radians in space, whereas

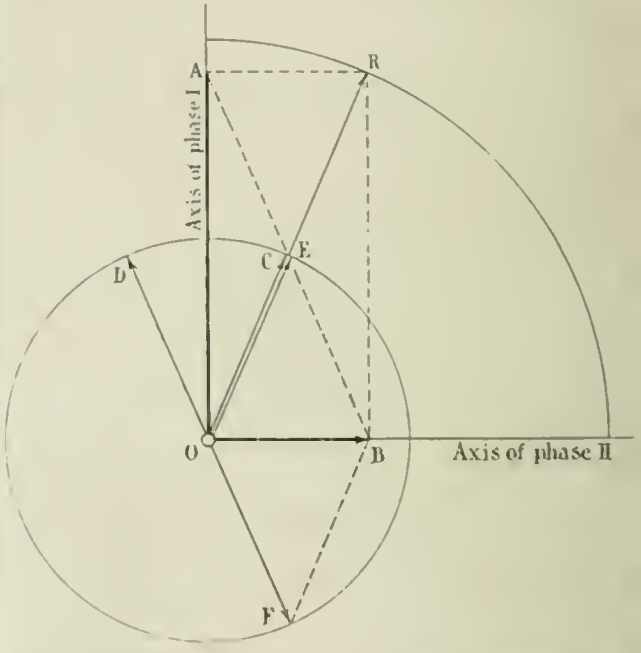

FIG. 5.—Resultant M.M.F. due to a two-phase system ; sinusoidal distribution and sine currents assumed.

O A and O B are values of M.M.F.'s due to phases I and II respectively ;
O C and O E are the normal (clockwise) rotating components of phases I and II respectively ;
O D and O F are the inverse (anti-clockwise) rotating components of phases I and II respectively ;
O R is the resultant, constant (clockwise), rotating M.M.F.

the time displacement between the two currents is still one-quarter of a period. Hence the displacement between the normal rotating components for the third harmonics is $3\pi/2 - \pi/2 = \pi$, and hence the components are in exact opposition and neutralize each other. With the inverse rotating components, however, the displacement is $3\pi/2 - (-\pi/2)$, i.e. $= 2\pi$, and hence the inverse rotating components of the third harmonics of the two phases are in conjunction. As a result, the joint effect of the third harmonics in the M.M.F. distribution-forms of the arma-

ture windings on a two-phase machine is equivalent to an M.M.F. of sinusoidal distribution, and constant amplitude, rotating in the opposite direction to the main exciting winding at one-third of normal speed.

So far as the rotor is concerned, then, the third harmonics are equivalent to an M.M.F. of 3 times the normal number of poles, moving backward, relatively to the rotor, at 4/3 of normal speed. Electromotive forces and currents of 4 times the normal frequency will therefore be induced in the amortisseurs, if any, or, in the absence of proper amortisseurs, in the rotor iron and the main exciting winding. Generally, the construction of cylindrical-field machines is such that an efficient damping action is set up and the exciting winding is screened from the effect of the third and higher harmonics. If, however, the damping action is negligible, the fluctuations in the exciting current, of 4 times the normal frequency, will give rise to third and fifth harmonics in the armature current wave on short-circuit, and the virtual value of the current may be affected by perhaps one-half per cent or more.

With the fifth harmonics of the M.M.F. waves due to the two phases, the two normal rotating components are in conjunction and the inverse components in opposition. The resulting rotating M.M.F., of sinusoidal distribution, due to the fifth harmonics in the M.M.F. waves, therefore moves at one-fifth of normal speed in the normal direction. The fifth harmonies therefore also tend to establish currents of 4 times the normal frequency in the rotor iron and windings.

Similarly the seventh and ninth harmonics in the M.M.F. waves tend to induce currents of 8 times normal frequency in the rotor circuits, and, unless the damping is efficient, currents of the seventh and ninth orders will be induced in the armature winding—and so on.

The higher harmonics in the M.M.F. distribution, therefore, serve simply to provide the irregularities in the actual rotating M.M.F. produced by the joint action of the two phases; the effect of these irregularities is neutralized by the currents induced in the rotor iron, slot wedges, etc., and they have no appreciable effect upon the value of the short-circuit current of cylindrical-field alternators of normal construction.

As a result, for a two-phase cylindrical-field alternator, the effect of the armature reaction may be taken as due simply to the combined effect of the two normally rotating components of the fundamental harmonics in the M.M.F. distribution-forms of the two phases. The reaction is thus equivalent to a steady sinusoidal M.M.F., equal to the maximum value of the fundamental harmonic of the M.M.F. due to one phase, and is in opposition to, and rotating in synchronism with, the exciting winding.

Thus, amplitude of the equivalent sinusoidal M.M.F. for the armature winding with two-phase machines

$$=\frac{4}{\pi}\times\frac{\sin\beta}{\beta}\,\mathrm{N\,I}\sqrt{2}*$$

(3) *Three-phase machines.*—Proceeding on similar lines to those adopted in dealing with two-phase machines, the M.M.F. distribution-forms of the three phases at any instant may be represented by the three series:

M.M.F. due to phase 1:

$$y_1=\frac{4}{\pi}\times\frac{\mathrm{N\,I}\sqrt{2}}{\beta}\sin\left(wt+\frac{2\pi}{3}\right)\left\{\sin\beta\sin\left(\theta+\frac{2\pi}{3}\right)+\frac{1}{9}\sin 3\beta\sin 3\left(\theta+\frac{2\pi}{3}\right)+\ldots\right\}$$

M.M.F. due to phase 2:

$$y_2=\frac{4}{\pi}\times\frac{\mathrm{N\,I}\sqrt{2}}{\beta}\sin wt\left\{\sin\beta\sin\theta+\frac{1}{9}\sin 3\beta\sin 3\theta+\ldots\right\}$$

M.M.F. due to phase 3:

$$y_3=\frac{4}{\pi}\times\frac{\mathrm{N\,I}\sqrt{2}}{\beta}\sin\left(wt-\frac{2\pi}{3}\right)\left\{\sin\beta\sin\left(\theta-\frac{2\pi}{3}\right)+\frac{1}{9}\sin 3\beta\sin 3\left(\theta-\frac{2\pi}{3}\right)+\ldots\right\}$$

The magnetomotive forces of the three phases are displaced, respectively, by one-third of a period in time, and by one-third of the double pole-pitch in space, and, for a normal winding, $\beta=\pi/6$.

Again the effects of the various harmonics in the M.M.F. forms can be considered separately.

With the fundamental harmonies the normal rotating components are exactly in step, so that their effects add up. The inverse rotating components are, however, displaced respectively by $2\pi/3$ radians, so that their joint effect is zero. As a result, so far as the fundamental harmonics are concerned, the joint effect of the three phases is to produce a synchronous rotating M.M.F., of sinusoidal distribution and in opposition to the main M.M.F. The amplitude of this sinusoidal M.M.F. is $1{\cdot}5\times\frac{4}{\pi}\cdot\frac{\sin\beta}{\beta}\,\mathrm{N\,I}\sqrt{2}$.

So far as the higher harmonics are concerned, there is no great difference from the case of two-phase windings, with the important exception of the action of the harmonics of the third orders. The space displacement between the windings corresponds to $3\times 2\pi/3$, i.e. 2π radians for the third harmonics. That is, the axes of these magnetomotive forces are the same for all three phases. The algebraic sum of the currents in the three phases being zero at every instant, the joint effect of all harmonics of the third order is therefore zero.

It is due to this neutralizing of the third harmonics that the rotating M.M.F. produced by a normal three-phase winding is more uniform than that due to a two-phase winding.

The effect of the higher harmonics in the M.M.F. distribution wave-forms is so small with three-phase machines that, even if the rotor is not provided with anything in the nature of amortisseurs, the higher harmonics have no effect of any practical importance upon the value of the short-circuit current.

As a result, for a three-phase cylindrical-field alternator the effect of the armature reaction may be taken as equivalent to a steady sinusoidal M.M.F., equal in magnitude to 1·5 times the maximum value of the fundamental harmonic of the M.M.F. for one phase, in opposition to and rotating in synchronism with the exciting winding.

* Since $\beta=\pi/4$, for a normal two-phase winding, the expression for the amplitude of the equivalent sinusoidal M.M.F. reduces to $\frac{16}{\pi^2}\,\mathrm{N\,I}$. It is convenient, however, to retain the same type of formula as the one holding good for single-phase machines.

Thus, the amplitude of the equivalent sinusoidal M.M.F. for the armature winding, with three-phase machines

$$= 1{\cdot}5 \times \frac{4}{\pi} \cdot \frac{\sin \beta}{\beta} N I \sqrt{2}$$

IV. Practical Application.

In the above it has been shown that, so far as the value of the short-circuit current of cylindrical-field alternators is concerned, the effects of the magnetomotive forces of the armature windings and of the exciting windings are the same as those of sinusoidal distribution having the following amplitudes:

Main exciting winding	$\frac{4}{\pi} \cdot \frac{\sin \beta_e}{\beta_e} N_e I_e$
Armature winding:	
Single-phase	$0{\cdot}5 \times \frac{4}{\pi} \cdot \frac{\sin \beta}{\beta} N I \sqrt{2}$
Two-phase	$1{\cdot}0 \times \frac{4}{\pi} \cdot \frac{\sin \beta}{\beta} N I \sqrt{2}$
Three-phase	$1{\cdot}5 \times \frac{4}{\pi} \cdot \frac{\sin \beta}{\beta} N I \sqrt{2}$

These expressions could be used as they stand. It is, however, of great convenience in practice to work in terms of $N_e I_e$, the actual total value of the ampere-turns of the field winding, and to obtain an "equivalent value" for the armature M.M.F.

These equivalent values are obtained simply by dividing the value of the amplitude of the M.M.F. concerned by the factor $\frac{4}{\pi} \times \frac{\sin \beta_e}{\beta_e}$ and become:

Main extension winding	$N_e I_e$
Armature winding:	
Single-phase	$0{\cdot}5 \frac{\beta_e}{\beta} \cdot \frac{\sin \beta}{\sin \beta_e} N I \sqrt{2}$
Two-phase	$1{\cdot}0 \frac{\beta_e}{\beta} \cdot \frac{\sin \beta}{\sin \beta_e} N I \sqrt{2}$
Three-phase	$1{\cdot}5 \frac{\beta_e}{\beta} \cdot \frac{\sin \beta}{\sin \beta_e} N I \sqrt{2}$

In working out the value of the ratio of the winding factors it is immaterial whether β_e and β are taken in radians or in degrees.

For three-phase windings: $\beta = \pi/6 = 30°$; $\sin \beta = 0{\cdot}500$;
For two-phase windings: $\beta = \pi/4 = 45°$; $\sin \beta = 0{\cdot}707$;
For single-phase, 2/3 winding: $\beta = \pi/3 = 60°$; $\sin \beta = 0{\cdot}866$.

The "equivalent spread factor" $\frac{\beta_e}{\beta} \cdot \frac{\sin \beta}{\sin \beta_e}$ can thus be readily calculated for any given spread of the main exciting winding. Table 2 gives the results of such calculations for exciting windings of spreads varying from 45° to 90°, and Fig. 6 gives the results in a form suitable for use in a design office.

A further amplification is possible by basing the calculation of the armature M.M.F. upon the value of the total ampere-turns per pole on the armature, rather than the value per phase of the winding. It is then no longer necessary to have different constants (1, 2, and 3) when dealing with single-, two-, and three-phase windings.

The value of the equivalent armature M.M.F. may be expressed thus:

Armature M.M.F. per pole

$$= \left\{0{\cdot}25 \frac{\beta_e}{\beta} \cdot \frac{\sin \beta}{\sin \beta_e} \sqrt{2}\right\} \times \text{ampere-conductors per pole}$$

. . . ampere-turns,

$= K_e \times$ ampere-conductors per pole . . . ampere-turns.

Let $\tau =$ the pole-pitch in cm.,
and $q =$ the value of the "ampere-conductors" per cm. of the armature circumference, calculated as the mean value over the whole pole-pitch on the basis of the virtual value of the armature current.

Then, armature M.M.F. per pole $= K_e \tau q$ . . . ampere-turns.

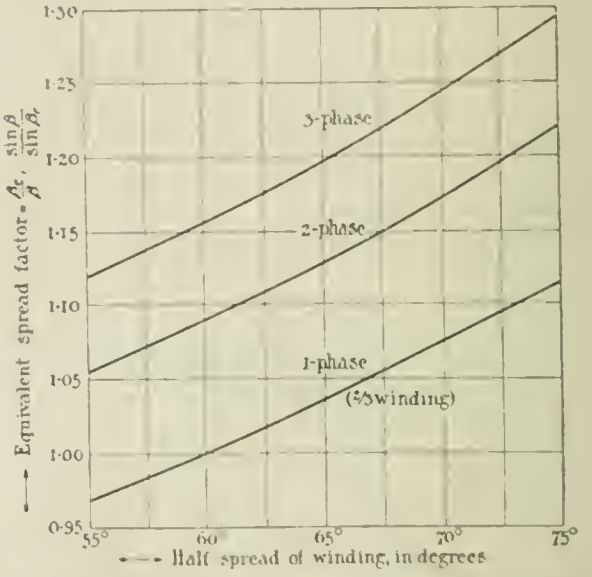

Fig. 6.—Equivalent spread factors, for single and polyphase windings and various angles of "spread" of the exciting winding.

From certain points of view there are many advantages in calculating the performance of machines in terms of their magnetic and electric loading constants.*

Table 2A gives the values of this constant $K_e \left(= 0{\cdot}25\sqrt{2} \frac{\beta_e}{\beta} \cdot \frac{\sin \beta}{\sin \beta_e}\right)$ for various values of β_e, and for single-phase and polyphase machines.

In cases where the designer prefers to work out the performance from the point of view of the machine as a whole, the value of the equivalent armature M.M.F. may be expressed in the form:

Armature M.M.F. per pole $= K_e \frac{I_a Z_a}{\text{No. of poles}}$ . . . ampere-turns

where Z_a is the total number of conductors on the armature, i.e. the product of the total number of slots and the number of conductors per slot,
and I_a is the virtual value of the current per conductor.

* A. E. Clayton: "On the Design of Dynamo Electric Machinery," *Electrician* 1912, vol. 68, pp. 974 and 1007.

Expressed in either of the above forms, both being independent of the number of phases, the calculation of the value of the armature reaction under steady short-circuit conditions becomes a matter of extreme simplicity.

In dealing with the actual performance of a cylindrical-field alternator under steady short-circuit conditions, it is thus convenient to plot the magnetization curves in terms

TABLE 2.

Values of the "Equivalent Spread Factor" for Single-, Two- and Three-phase Cylindrical-field Alternators, for Various Spreads of the Exciting Winding.

Half Spread of Winding, in Degrees	$(1/\beta_e)\sin\beta_e$	Equivalent Spread Factor $= \frac{\beta_e}{\beta}\cdot\frac{\sin\beta}{\sin\beta_e}$		
		Single-phase (2/3 winding)	Two-phase	Three-phase
45	0·9003	0·9186	1·0000	1·0607
50	0·8778	0·9421	1·0256	1·0878
55	0·8533	0·9691	1·0551	1·1191
60	0·8270	1·0000	1·0887	1·1547
65	0·7987	1·0352	1·1266	1·1953
70	0·7691	1·0753	1·1706	1·2418
75	0·7379	1·1207	1·2201	1·2941
80	0·7053	1·1725	1·2674	1·3539
85	0·6715	1·2315	1·3392	1·4220
90	0·6366	1·2990	1·4142	1·5000

TABLE 2A

Values of the Armature-reaction constant K_r, for Single-, Two-, and Three-phase Cylindrical-field Alternators, for Various Spreads of the Main Exciting Winding and for Full-pitch Armature Windings.

Half Spread of Exciting Winding, in Degrees	Armature Reaction Constant, $K_r = 0{\cdot}25\sqrt{2}\,\frac{\beta_e}{\beta}\cdot\frac{\sin\beta}{\sin\beta_e}$		
	Single-phase (2/3 winding)	Two-phase	Three-phase
45	0·3248	0·3535	0·3750
50	0·3330	0·3627	0·3845
55	0·3426	0·3730	0·3956
60	0·3535	0·3849	0·4082
65	0·3660	0·3983	0·4226
70	0·3801	0·4138	0·4390
75	0·3962	0·4313	0·4575
80	0·4145	0·4481	0·4784
85	0·4354	0·4734	0·5028
90	0·4593	0·5000	0·5303

of the actual maximum value of the main exciting M.M.F., $N_e I_e$, and to calculate the equivalent value of the armature reaction in the manner indicated above.

Thus, in Fig. 1,

If I_e is the exciting current necessary to maintain normal full-load current in the armature under steady short-circuit conditions,

and q is the specific electric loading on the armature at normal full load,

O A is made to represent $N_e I_e$ to scale,

and A B is made to represent $K_r \tau q$ to scale.

V. Fractional-pitch Windings.

Fractional-pitch windings are often used in practice, especially in the case of two-pole machines, as they offer certain advantages, which need not be discussed here.

The M.M.F. distribution due to a single, concentrated, fractional-pitch coil, there being one such coil per pole, would be as shown in Fig. 7. This wave-form may be represented by the Fourrier series:

$$y = \frac{4}{\pi}\cdot Y\left\{\sin\alpha\sin\theta + \frac{1}{3}\sin 3\alpha\sin 3\theta + \ldots\right\}$$

In this expression: α represents one-half of the span of the coil, and is therefore equal to $F\,\pi/2$, where F denotes the fraction of the pole-pitch spanned by the coil.

The fundamental harmonic thus has a maximum amplitude of $\sin\alpha \cdot 4\,Y/\pi$ instead of the value $4\,Y/\pi$ obtaining for a full-pitch coil.

Hence, in the case of fractional-pitch windings, it is simply necessary to introduce the factor $\sin\alpha$ into the

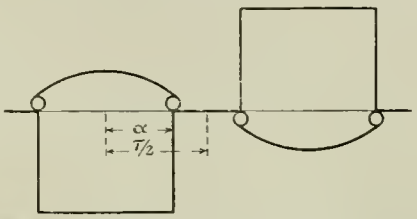

FIG. 7.—M.M.F. distribution due to a concentrated, fractional-pitch winding.

expressions already obtained for the equivalent armature M. M. F., with full-pitch coils.

Thus, equivalent value of the armature M.M.F. for a fractional-pitch winding

$$= 0{\cdot}25\sin\alpha\left(\frac{\beta_e}{\beta}\cdot\frac{\sin\beta}{\sin\beta}\right)\tau q\sqrt{2}$$

$$= (\sin\alpha)\,K_r\,\tau\,q$$

A further point of interest occurs in the case of these fractional-pitch windings, and that is, it is possible, by adjusting the span of the coils, to eliminate any particular higher harmonic from the M.M.F. distribution of each phase of the armature winding. The condition to be fulfilled for the elimination of the nth harmonic is simply that $\sin(n\alpha) = 0$. To eliminate the third harmonic, for example, it is thus necessary to choose a value of α such that $\sin 3\alpha$ is zero, and therefore 3α is equal to 180°, and α to 60°. The span of the winding, in order that third harmonics shall not be present, is therefore two-thirds of a complete pole-pitch. Similarly, the fifth harmonic is absent when the span is two-fifths or four-fifths of a complete pole-pitch.

Since the irregularities in the rotating M.M.F. of two-phase windings are largely due to the effects of the third harmonic in the phase M.M.F. distribution wave, it follows that by adopting a winding with a fractional pitch of two-thirds for two-phase armatures, the rotating M.M.F. set up will be nearly as constant as in the case of three-phase windings. Fig. 8*a* shows the M.M.F. distribution per phase for such a winding; Fig. 8*b* the limiting values

of the total M.M.F. due to the joint action of the two phases; and Fig. 8c the corresponding limiting values for a normal full-pitch two-phase winding.

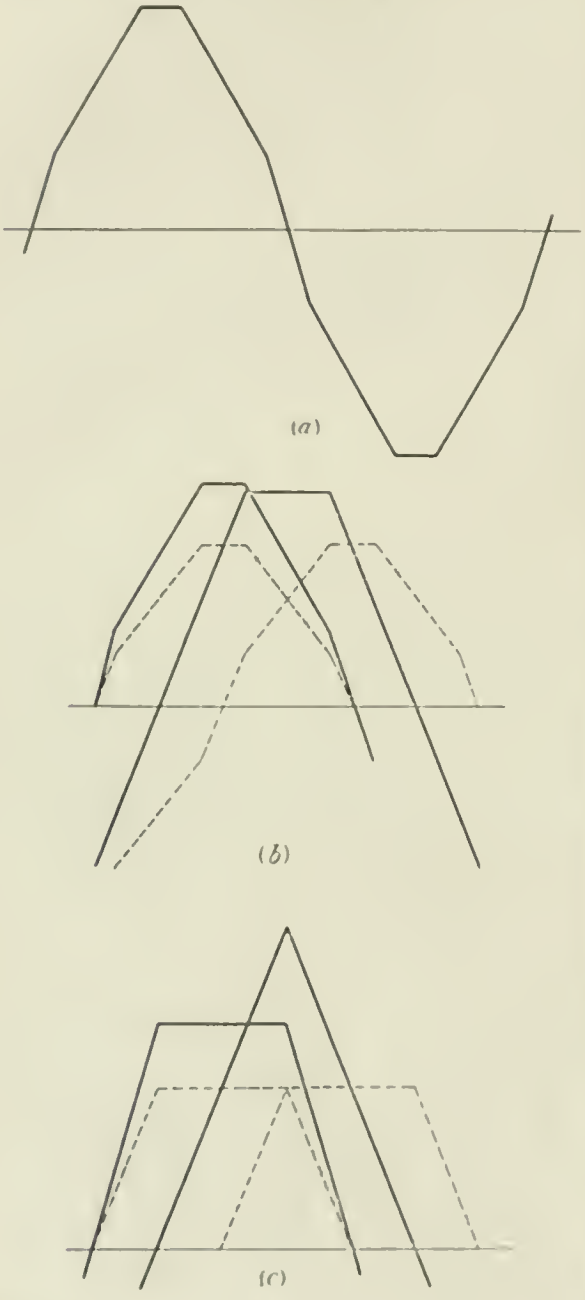

FIG. 8.
(*a*) M.M.F. distribution per phase for a two phase fractional pitch winding, with $\alpha = \pi/3$.
(*b*) and (*c*) Limiting M.M.F. wave-shapes for two-phase windings: (1) fractional pitch, 2/3 winding, (2) normal full-pitch winding.

VI. Unbalanced Polyphase Machines.

Cylindrical-field alternators are frequently wound with coil-type windings, with the end connections of the coils in two or three ranges. As a result it sometimes happens that the reactance of the winding has not the same value for the various phases. The current obtained on short-circuit, under such conditions, no longer has the same value in each of the phases.

In dealing with a case of this nature, the same method of treatment can be employed as that adopted with the normal balanced machines.

Dealing, for example, with the case of an unbalanced three-phase machine, the normal rotating components of the main harmonics are again in conjunction, and the inverse components are displaced respectively by $2\pi/3$ radians. The inverse components of the currents in the three phases, however, no longer have the same value, so that the inverse rotating components do not cancel out exactly. As a result the M.M.F. due to the main harmonics fluctuates slightly, and the machine will show traces of the performance of a single-phase alternator. Unless efficient damping devices are used on the field system, double-frequency currents will be set up in the main exciting winding, and traces of third harmonics will be established in the armature current. The fact that, with a star-connected machine the total spread of the winding between terminals corresponds to two-thirds of a pole-pitch, does not prevent these triple-frequency currents from being established in such an unbalanced machine on short-circuit. The author has shown* that such triple-frequency currents are set up in armature windings, quite independent of their spread, when double-frequency currents flow in the exciting winding.

FIG. 9.—Current wave for an unbalanced three-phase alternator on steady short-circuit.

This effect can be seen in Fig. 9, which represents the actual current wave-form obtained on short-circuit with a cylindrical-field alternator the three phases of which were slightly unbalanced for the reasons given above.

The higher harmonics induced, however, have no appreciable effect upon the virtual value of the armature currents and, in dealing with the case in which the currents in the phases have different values, it is sufficient to consider simply the normal rotating components of the fundamental harmonics.

It is therefore sufficient to use the formulæ already given, and to take the value of the armature current as being the average value of the actual currents in the three windings.

VII. Irregularly Distributed Windings.

On rare occasions with cylindrical-field alternators, some of the slots in the stator may contain a reduced number of conductors; it may also happen with solid rotors that the slotting may be irregular.

The fundamental harmonic of the M.M.F. waves obtaining under these conditions can readily be deduced by using the formulæ developed in paragraphs (*b*) and (*c*) of Section II of the Appendix.

* A. E. Clayton, "The Wave Shapes obtaining with Alternating-current Generators under Steady Short-circuit Conditions," *Journal I.E.E.*, 1916, vol. 54, p. 100.

The value to take for the equivalent armature M.M.F. under either of these conditions can thus be calculated without much difficulty.

VIII. Comparison with Other Methods.

Of the other methods of dealing with armature reaction in cylindrical-field machines, some are frankly empirical and need not be discussed, and perhaps the most common method having a logical basis is to deal with the mean values of the various magnetomotive forces over the complete pole-pitch. Such a method has much in its favour: it is easy to follow, and, to the average mind, is no doubt less abstract than one which deals only with the fundamental harmonics of the various magnetomotive forces.

Now it has been shown quite conclusively that, for the particular case of a cylindrical-field alternator working under normal short-circuit conditions, it is correct to consider simply the fundamental harmonics of the various M.M.F. waves in calculating the value of the armature reaction. By dealing with the mean value of the actual M.M.F. waves over the whole pole-pitch, not only is the mean effect of the fundamental harmonic included, but also the mean values of all the higher harmonics over the complete pole-pitch. An indication of the error introduced by considering the mean value of the M.M.F. waves, instead of dealing only with their fundamental harmonics, can therefore be obtained by determining the difference between the mean value of the actual M.M.F. wave and that of its fundamental harmonic over one complete pole-pitch. For the armature it is necessary to consider further the mean value of the M.M.F. obtaining throughout the period—in time—as this M.M.F. is not constant, even with two-phase and three-phase machines.

Main magnetomotive force.—Dealing first with the main M.M.F., this wave is represented by the series:

$$x = \frac{4}{\pi} N_e I_e \frac{1}{\beta_e} \left\{ \sin \beta_e \sin \theta + \frac{1}{9} \sin 3\beta_e \sin 3\theta + \frac{1}{25} \sin 5\beta_e \sin 5\theta + \ldots \right\}$$

The area of this wave over one complete pole-pitch is given by $\int_0^\pi x \, d\theta$, and the mean value of the M.M.F. thus becomes:

$$x_{\text{mean}} = \frac{1}{\pi} \int_0^\pi x \, d\theta$$

$$= -\frac{4}{\pi^2} \times N_e I_e \frac{1}{\beta_e} \left[\sin \beta_e \cos \theta + \frac{1}{27} \sin 3\beta_e \cos 3\theta + \frac{1}{125} \sin 5\beta_e \cos 5\theta + \ldots \right]_0^\pi$$

$$= \frac{8}{\pi^2} \times N_e I_e \frac{1}{\beta_e} \left\{ \sin \beta_e + \frac{1}{27} \sin 3\beta_e + \frac{1}{125} \sin 5\beta_e + \ldots \right\}$$

The total error introduced by dealing with the mean value of all the harmonics, instead of solely that of the fundamental, is therefore:

$$\frac{1}{\sin \beta_e} \left\{ \frac{1}{27} \sin 3\beta_e + \frac{1}{125} \sin 5\beta_e + \ldots \right\} \times 100, \text{ per cent}$$

The influence of the higher harmonics upon the mean value of the M.M.F. is thus reduced according to the order of the harmonic. In general, for an nth harmonic of A_n per cent in the M.M.F. wave, the mean value of the M.M.F. over the complete pole-pitch is increased or decreased by A_n/n per cent according to the sign of the harmonic.

The percentage error introduced by including any particular higher harmonic is therefore given by:

Percentage error due to the inclusion of the nth harmonic

$$= \frac{1}{n^3} \times \frac{\sin n\beta}{\sin \beta_e} \times 100$$

The error can therefore readily be calculated for various values of the spread of the winding.

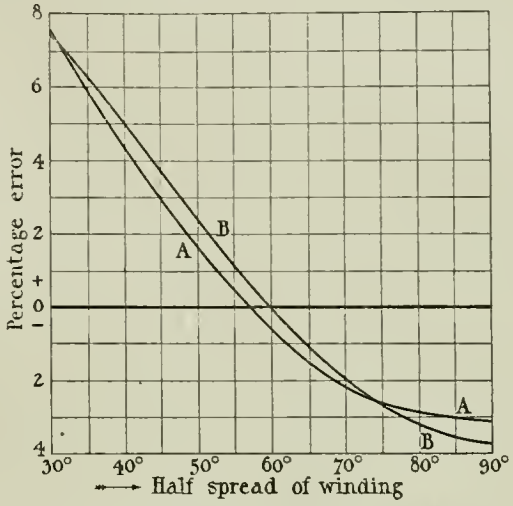

Fig. 10.—Error in the value of the main M.M.F., due to the inclusion of the higher harmonics.
Curve A gives the total effect of all the harmonics; Curve B the effect of the third harmonic.

Further, the mean value of the main M.M.F., including the effects of all the higher harmonics, can be obtained from the mean height of the trapezium wave-form and is equal to:

$$x_{\text{mean}} = (1 - \beta_e/\pi) N_e I_e$$

The mean value of the fundamental harmonic is equal to:

$$(8/\pi^2) \left(\frac{\sin \beta_e}{\beta_e} \right) N_e I$$

The percentage error due to the inclusion of the effects of all the higher harmonics can thus be calculated.

Table 3 shows the effect of the individual higher harmonics upon the mean value of the M.M.F. for various values of the spread of the winding. It also shows the total error introduced due to the combined action of all the higher harmonics.

The great importance of the third harmonic is very apparent. For small angles of spread of the winding, the third, fifth, seventh, and ninth harmonics all have the same sign, and their joint effect is very great. Such small angles of spread are, however, not normally in use.

For a two-thirds winding, i.e. for $\beta = \pi/3$, the third harmonic is zero, and the error introduced by dealing with the mean value of the actual M.M.F., instead of its fundamental harmonic, is negligible. For β = one radian the joint effect of all the higher harmonics upon the mean value of the M.M.F. is zero. For values of β less than one radian, the error is positive, i.e. too large a value is obtained, and for values of β greater than one radian the error is negative, the calculated M.M.F. being now too small.

Fig. 10 indicates the error introduced by calculating the M.M.F. upon the basis of the mean value of the actual distribution-form, instead of dealing solely with the fundamental harmonic.

Armature magnetomotive force.—Let us now deal with the armature M.M.F.

(*a*) *Single-phase machines.*—With single-phase machines the armature M.M.F. has its limiting values when the current is maximum and zero respectively.

constant rotating components, each of one-half the maximum amplitude of the alternating M.M.F. and of the same wave shape, and rotating in opposite directions at synchronous speed. This method of treatment is fundamentally unsound. For the theorem concerned to hold good in a case of this nature, not only is it necessary that the current shall be sinusoidal, but, in addition, the M.M.F. distribution-form must also be sinusoidal. To illustrate this point, Fig. 11 has been drawn, showing the resulting field distribution obtained at various instants, by combining two magnetomotive forces of normal trapezoidal wave-form rotating at synchronous speed in opposite directions. The wave shape obtained is far from constant, showing that the actual alternating M.M.F. cannot be replaced by two such rotating magnetomotive forces.

Nevertheless, so far as the fundamental harmonic is concerned, the method is correct. So that the error obtained in determining the value of the armature M.M.F.

TABLE 3.

The Effect of the Various Harmonics upon the Mean Value of the M.M.F. over One Complete Pole-pitch, for Various Spreads of the Exciting Winding.

Half Spread of Exciting Winding, in Degrees	Effect of Harmonic on Mean Value of M.M.F. Fundamental taken as 100						
	Fundamental Harmonic	Third Harmonic	Fifth Harmonic	Seventh Harmonic	Ninth Harmonic	Eleventh Harmonic	Total of All Harmonics
0	100	11·1	4·0	2·05	1·25	0·85	123·4
10	100	10·6	3·5	1·6	0·8	0·4	117·2
20	100	9·4	2·3	0·5	0	−0·15	111·9
30	100	7·4	0·8	−0·3	−0·3	−0·08	107·6
40	100	4·95	−0·4	−0·45	0	0·1	104·4
50	100	2·4	−0·95	−0·1	0·2	−0·02	101·6
60	100	0	−0·8	0·3	0	−0·08	99·5
70	100	−1·95	−0·15	0·25	−0·15	0·08	97·7
80	100	−3·25	0·5	−0·1	0	0·03	97·1
90	100	−3·7	0·8	−0·3	0·15	−0·08	96·9

Maximum value of armature M.M.F. is represented by:

$$y_{max.} = \frac{4}{\pi} \cdot \frac{1}{\beta} N I \sqrt{2} \left\{ \sin \beta \sin \theta + \frac{1}{9} \sin 3\beta \sin 3\theta + \dots \right\}$$

Minimum value of armature M.M.F. is represented by $y_{min.} = 0$.

Mean value of armature M.M.F. is represented by:

$$y_{mean} = \frac{8}{\pi^2} \cdot \frac{1}{\beta} N I \sqrt{2} \left\{ \sin \beta \sin \theta + \frac{1}{9} \sin 3\beta \sin 3\theta + \dots \right\}$$

since the mean value of $i = \frac{2}{\pi} N I \sqrt{2}$.

In dealing with the mean value of the M.M.F. waves, the most obvious procedure would be to calculate on the basis of the mean value of the M.M.F. series as given above. Such a method would give rise to very considerable errors, as the amplitude of the fundamental harmonic would be considerably in excess of the correct value.

In applying this method in actual practice, it is, however, not usual to deal with the actual mean value of the armature M.M.F. over the complete pole-pitch. Instead, it is usual to resolve the actual alternating M.M.F. into two

of single-phase alternators by this method is simply, as in the case of the main exciting winding, due to the difference between the mean values of the actual M.M.F. wave and that of its fundamental harmonic.

Table 3 and Fig. 10 therefore hold good, in addition, for the case of the armature winding of a single-phase cylindrical-field alternator. For most single-phase machines the spread of the winding is such that $\beta = \pi/3$, and the error in the value of the armature M.M.F. as determined by the method under consideration is only 0·6 per cent.

(*a*) *Polyphase machines.*—In obtaining the mean value of the armature M.M.F. for polyphase windings it is usual, and sufficient, to take the average of the values obtaining under the two limiting conditions.

(*b*) *Two-phase machines.*—With a two-phase winding, the armature M.M.F. has its limiting values when the current has the same value in the two phases, and when one phase only is active, respectively.

When one phase only is active, the current in that phase has its maximum value, and the M.M.F. wave is represented by the series:

$$y = \frac{4}{\pi} Y \cdot \frac{1}{\beta} \left\{ \sin \beta \sin \theta + \frac{1}{9} \sin 3\beta \sin 3\theta + \dots \right\}$$

In this series, $Y = N I \sqrt{2}$, and $\beta = \pi/4$. Hence

$$= \frac{16}{\pi^2} N I \left\{ \sin\theta + \frac{1}{9}\sin 3\theta - \frac{1}{25}\sin 5\theta - \frac{1}{49}\sin 7\theta + \ldots \right\}$$

The higher harmonics in this wave are therefore of considerable importance.

When the two phases are equally active, the current is 0·707 of its maximum value, and the magnetomotive forces of the two phases are represented respectively by the two series :

M.M.F. of phase 1 :

$$y_1 = 0{\cdot}707 \times \frac{16}{\pi^2} N I \left\{ \sin\theta + \frac{1}{9}\sin 3\theta - \frac{1}{25}\sin 5\theta - \frac{1}{49}\sin 7\theta + \ldots \right\}$$

and M.M.F. of phase 2 :

$$y_2 = 0{\cdot}707 \times \frac{16}{\pi^2} N I \left\{ \sin\left(\theta + \frac{\pi}{2}\right) + \frac{1}{9}\sin 3\left(\theta + \frac{\pi}{2}\right) - \frac{1}{25}\sin 5\left(\theta + \frac{\pi}{2}\right) - \ldots \right\}$$

The resulting M.M.F. distribution due to the combined action of the two phases is obtained by summing the two series given above, and becomes

$$\begin{aligned} y &= y_1 + y_2 \\ &= 0{\cdot}707 \times \frac{16}{\pi^2} N I \left\{ \sin\theta + \frac{1}{9}\sin 3\theta - \frac{1}{25}\sin 5\theta - \frac{1}{49}\sin 7\theta + \ldots \right\} \\ &\quad + 0{\cdot}707 \times \frac{16}{\pi^2} N I \left\{ \sin\left(\theta + \frac{\pi}{2}\right) + \frac{1}{9}\sin 3\left(\theta + \frac{\pi}{2}\right) - \frac{1}{25}\sin 5\left(\theta + \frac{\pi}{2}\right) + \ldots \right\} \\ &= \frac{16}{\pi^2} N I \left\{ \sin\left(\theta + \frac{\pi}{4}\right) - \frac{1}{9}\sin 3\left(\theta + \frac{\pi}{4}\right) + \frac{1}{25}\sin 5\left(\theta + \frac{\pi}{4}\right) - \frac{1}{49}\sin 7\left(\theta + \frac{\pi}{4}\right) + \frac{1}{81}\sin 9\left(\theta + \frac{\pi}{4}\right) + \ldots \right\} \end{aligned}$$

Again the higher harmonics are of considerable importance. The wave-form is now of the well-known triangular form shown in Fig. 12*b*.

The wave-form representing the average of the two limiting conditions is obtained from the average value of the two series given below, viz.

$$y = \frac{16}{\pi^2} N I \left\{ \sin\theta + \frac{1}{9}\sin 3\theta - \frac{1}{25}\sin 5\theta - \frac{1}{49}\sin 7\theta + \ldots \right\}$$

and

$$y = \frac{16}{\pi^2} N I \left\{ \sin\theta - \frac{1}{9}\sin 3\theta + \frac{1}{25}\sin 5\theta - \frac{1}{49}\sin 7\theta + \ldots \right\}$$

This "average" wave-form is thus represented by the series :

$$y = \frac{16}{\pi^2} N I \left\{ \sin\theta - \frac{1}{49}\sin 7\theta + \frac{1}{81}\sin 9\theta - \ldots \right\}$$

This series corresponds to the wave-form shown in Fig. 12*c*; its small deviation from the fundamental harmonic is noteworthy.

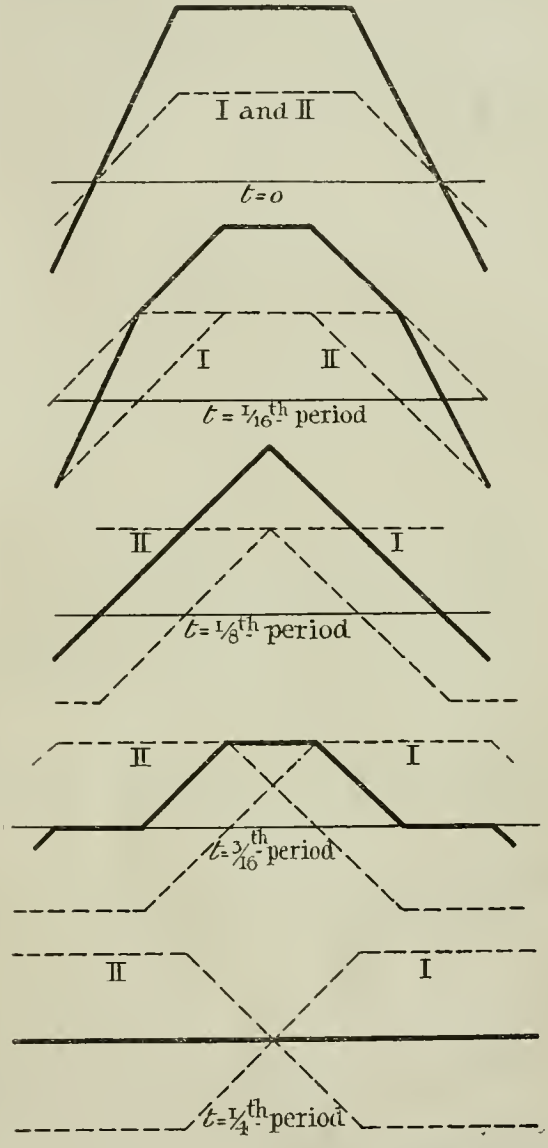

FIG. 11.—Effect of combining two constant M.M.F.'s of trapezium wave-shape, rotating in opposite directions at synchronous speed.

It thus appears that in the case of a two-phase armature, in each of the limiting wave-shapes of the M.M.F. distribution—the trapezium and the triangle—the higher harmonics are of considerable importance. Further, the amplitudes of the corresponding harmonics have the same value in the two cases, but with those of the third and

fifth, eleventh and thirteenth, etc., orders, the signs are opposite in the two waves.

As a result, for a two-phase machine the average M.M.F. distribution obtained by taking the mean of the two extreme conditions is devoid of third and fifth harmonics, and the effect of those of still higher orders upon the mean value over the complete pole-pitch is absolutely negligible.

So that the mean value of the armature M.M.F., as determined by the mean of the values existing under the two limiting conditions, is practically exactly equal to the mean ordinate of the constant fundamental harmonic. No error is therefore introduced by determining the value of the armature M.M.F. of a two-phase alternator by this method.

FIG. 12.—Two-phase M.M.F. distribution-forms.

a and *b* are two limiting forms;
c represents the "average" of the two limiting conditions;
d represents the constant fundamental harmonic;
o denotes a point on the "average" distribution-form.

Table 4 gives the values of the amplitudes of the several higher harmonics for the various wave-forms occurring with two-phase windings.

TABLE 4.

Amplitudes of the Various Harmonics in the M.M.F. Wave-forms obtaining with a Two-phase Winding.

Order of Harmonic	Amplitude			
	Phase M.M.F.	Current Max. in One Phase	Currents Equal in Phases I and II	Mean of Limiting M.M.F. Waves
1	100	100	100	100
3	11·1	11·1	−11·1	0
5	−4·0	−4·0	4·0	0
7	−2·04	−2·04	−2·04	−2·04
9	1·24	1·24	1·24	1·24
11	0·83	0·83	−0·83	0
13	−(0·6)	0·(6)	0·(6)	0
15	−0·44	−0·44	−0·44	−0·44
17	0·35	0·35	0·35	0·35
19	0·28	0·28	0·28	0
21	−0·23	−0·23	0·23	0

(c) *Three-phase machines.*—With three-phase alternators, the armature M.M.F. has its limiting values when the current in one of the phases is maximum and zero, respectively.

The M.M.F. distribution due to one phase only, and with maximum current in that phase, is represented by the series:

$$y_1=\frac{4Y}{\pi}\left\{\sin\beta\sin\theta+\frac{1}{9}\sin 3\beta\sin 3\theta+\frac{1}{25}\sin 5\beta\sin 5\theta+\ldots\right\}$$

where $Y=NI\sqrt{2}$, and $\beta=\pi/6$.

Hence

$$y_1=\frac{12}{\pi^2}NI\sqrt{2}\left\{\sin\theta+\frac{2}{9}\sin 3\theta+\frac{1}{25}\sin 5\theta-\frac{1}{49}\sin 7\theta-\frac{2}{81}\sin 9\theta+\ldots\right\}$$

It will be noticed that the higher harmonics are of considerable importance in this series, owing to the small spread of the winding, and that the third harmonic is, in particular, very prominent.

When the current in one phase is maximum, its value in each of the other phases is one-half of the maximum and its sign is opposite to that in the first phase.

The M.M.F. distribution wave-forms of each of the three windings acting separately are represented respectively by the three series:

$$y_3=-0{\cdot}5\,\frac{12}{\pi^2}NI\sqrt{2}\left\{\sin\left(\theta-\frac{2\pi}{3}\right)-\frac{2}{9}\sin 3\left(\theta-\frac{2\pi}{3}\right)+\frac{1}{25}\sin 5\left(\theta-\frac{2\pi}{3}\right)+\ldots\right\}$$

$$y_2=\frac{12}{\pi^2}NI\sqrt{2}\left\{\sin\theta+\frac{2}{9}\sin 3\theta+\frac{1}{25}\sin 5\theta-\frac{1}{49}\sin 7\theta-\frac{2}{81}\sin 9\theta+\ldots\right\}$$

$$y_4=-0{\cdot}5\,\frac{12}{\pi^2}NI\sqrt{2}\left\{\sin\left(\theta+\frac{2\pi}{3}\right)-\frac{2}{9}\sin 3\left(\theta+\frac{2\pi}{3}\right)+\frac{1}{25}\sin 5\left(\theta+\frac{2\pi}{3}\right)+\ldots\right\}$$

The resulting M.M.F. distribution due to the combined action of the three windings is obtained by summing the above series, and thus becomes

$$y=y_1+y_2+y_3$$

$$=\frac{12}{\pi^2}NI\sqrt{2}\left\{1{\cdot}5\sin\theta+\frac{1{\cdot}5}{25}\sin 5\theta-\frac{1{\cdot}5}{49}\sin 7\theta-\frac{1{\cdot}5}{121}\sin 11\theta+\ldots\right\}$$

In the resulting M.M.F. distribution, of the roof form shown in Fig. 13*a*, the only higher harmonic of appreciable magnitude is the fifth, and those of the third order are absent.

When the current in one of the phases is zero, the

currents in the other two phases are equal to 0·866 of the maximum value and opposite in sign. The M.M.F. distribution-forms for the three phases under these conditions are represented respectively by the three series :

$$y_3 = 0$$

$$y_2 = 0{\cdot}866 \times \frac{12}{\pi^2} N I \sqrt{2} \left\{ \sin\theta + \frac{2}{9}\sin 3\theta + \frac{1}{25}\sin 5\theta + \dots \right\}$$

and $$y_1 = -0{\cdot}866 \times \frac{12}{\pi^2} N I \sqrt{2} \left\{ \sin\left(\theta + \frac{2\pi}{3}\right) + \frac{2}{9}\sin 3\left(\theta + \frac{2\pi}{3}\right) + \frac{1}{25}\sin 5\left(\theta + \frac{2\pi}{3}\right) + \dots \right\}$$

The total M.M.F. distribution due to the combined action of the three phases therefore becomes of the form represented by the series :

$$y = y_3 + y_2 + y_1$$

$$= \frac{12}{\pi^2} N I \sqrt{2} \left\{ 1{\cdot}5 \sin\left(\theta - \frac{\pi}{6}\right) - \frac{1{\cdot}5}{25}\sin 5\left(\theta - \frac{\pi}{6}\right) + \frac{1{\cdot}5}{49}\sin 7\left(\theta - \frac{\pi}{6}\right) - \frac{1{\cdot}5}{121}\sin 11\left(\theta - \frac{\pi}{6}\right) + \dots \right\}$$

Again all harmonics of the third order are absent, and the amplitudes of the fifth and seventh harmonics are small.

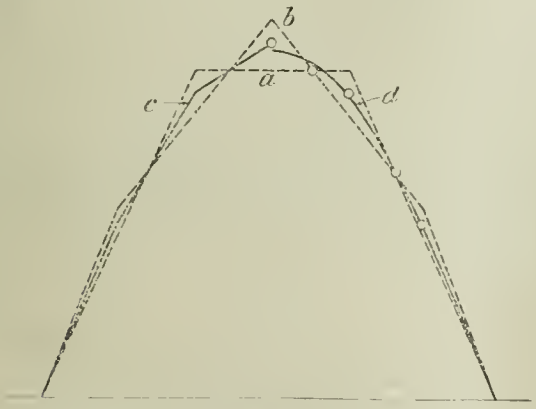

FIG. 13.—Three-phase M.M.F. distribution-forms.
a and *b* are the two limiting conditions ;
c is the average of the two limiting conditions ;
d is the constant fundamental harmonic ;
o denotes a point on the average distribution-form.

The M.M.F. distribution representing the average of those existing under the two limiting conditions in the case of three-phase windings is therefore given by the mean value of the two series :

$$y = \frac{12}{\pi^2} N I \sqrt{2} \left\{ 1{\cdot}5 \left(\sin\theta + \frac{1}{25}\sin 5\theta - \frac{1}{49}\sin 7\theta - \frac{1}{121}\sin 11\theta + \frac{1}{169}\sin 13\theta - \dots \right) \right\}$$

and $$y = \frac{12}{\pi^2} N I \sqrt{2} \left\{ 1{\cdot}5 \left(\sin\theta - \frac{1}{25}\sin 5\theta + \frac{1}{49}\sin 7\theta - \frac{1}{121}\sin 11\theta + \frac{1}{169}\sin 13\theta + \dots \right) \right\}$$

The mean value is thus represented by the series :

$$y = \frac{18}{\pi^2} N I \sqrt{2} \left\{ \sin\theta - \frac{1}{121}\sin 11\theta + \frac{1}{169}\sin 13\theta - \dots \right\}$$

The wave-shape corresponding to this mean M.M.F. distribution is shown in Fig. 13*c*. As in the case of the two-phase winding, the small deviation from the fundamental harmonic is very noteworthy. The higher harmonics cancel out almost entirely, the only higher harmonics present in the "mean" M.M.F. wave, as determined by the average of the two limiting conditions, being the eleventh and thirteenth, the twenty-third and twenty-fifth, etc.*

The total effect of all the harmonics upon the mean value of the M.M.F. over the complete pole-pitch is readily obtained from a consideration of the mean ordinate of the actual M.M.F. wave-shape.

Table 5 gives the values of the higher harmonics in the various M.M.F. waves occurring with three-phase windings.

For three-phase machines, then, the mean value of the armature M.M.F. as determined by the mean of the values obtaining under the two limiting conditions is almost exactly equal to the mean ordinate of the constant fundamental harmonic. As a result, no error is introduced by determining the value of the armature M.M.F. in this manner.

TABLE 5.

The Amplitudes of the Various Harmonics in the M.M.F. Wave-forms obtained with a Three-phase Winding.

Order of Harmonic	Amplitude for Various Waves in Fig. 13			
	Phase M.M.F.	Current Max. in One Phase	Current Zero in One Phase	Mean of Two Limiting Conditions
1	100	100	100	100
3	22·22	0	0	0
5	4·0	4·0	−4·0	0
7	−2·04	−2·04	2·04	0
9	−2·47	0	0	0
11	−0·83	−0·83	−0·83	−0·83
13	0·69	0·69	0·69	0·69
15	0·89	0	0	0
17	0·35	0·35	−0·35	0
19	−0·28	−0·28	0·28	0
21	−0·45	0	0	0

As a result of these investigations, it would appear that there is no appreciable difference between the mean ordinate of the armature M.M.F. as determined by the method under consideration and that of its constant fundamental harmonic for polyphase machines, and that for single-phase machines having a two-thirds winding the difference is small. On the other hand, in the case of the main exciting winding, the mean ordinate of the actual M.M.F. distribution-form may differ considerably from that of its fundamental harmonic, the difference depending upon the spread of the winding.

Hence, with cylindrical-field machines working under

* Cf. B. HAGUE : "The Mathematical Treatment of the Magnetomotive Force of Armature Windings," *Journal I.E.E.*, 1917, vol. 55, p. 490.

steady short-circuit conditions, an error of considerable importance may be introduced by calculating upon the basis of the mean values of the actual M.M.F. distribution-forms. The error being confined to the estimation of the value of the main or exciting M.M.F., the figures given in Table 3 will also indicate the total error due to this method.

With single-phase machines in which the spread of the armature winding is no longer such that $\beta \doteqdot$ one radian, a further error may be introduced. The total error in such a case can, however, readily be computed from Table 3 by combining the error in the estimation of the main M.M.F. with that in the estimation of the armature M.M.F. Thus, for example, in the case of a normal two-phase machine working single-phase, the spread of the rotor winding being such that $\beta = 70°$, the total error in the value of the equivalent armature M.M.F. would be made up as follows:

Calculated value of main M.M.F. is 0·978 of true value;
Calculated value of the armature M.M.F. is 1·03 of true value;
Hence equivalent value of the armature M.M.F. is $1·03/0·978 = 105·3$ per cent of the correct value.

Similarly, if the machine were worked single-phase with the two windings in series the equivalent value of the armature M.M.F. as calculated by this method would be 99·1 per cent of the correct value.

IX. Application to Normal Load Conditions.

When working under normal conditions of load, the saturation of the iron parts of the magnetic circuit, and magnetic leakage, result in any method such as this, which is based upon the fundamental harmonic of the various M.M.F. waves, being no longer exact.

However, for all ordinary purposes such as the calculation of the full-load excitation, etc., involving the use of a vector treatment, the value of the equivalent armature M.M.F. as obtained in this paper may certainly be used without any undue loss of accuracy.

Conclusion.

In this paper it has been shown that, for the particular case of a cylindrical-field alternator working under steady short-circuit conditions, it is correct to base the calculation of the main and armature magnetomotive forces solely upon the values of the fundamental harmonics of their wave-forms, and that, in consequence, a treatment on the lines of the method used by Arnold and Russell in dealing with the general problem of armature reaction is justified.

Further, it has been shown that no error is introduced in such calculations if, instead of dealing with the actual stepped M.M.F. wave shape, the corresponding trapezium wave-form, i.e. that obtaining for a surface winding of the same spread as the actual winding, is taken in place of the stepped wave.

To render the method suitable to actual practical conditions, in Section IV of the paper it is shown that the practical application is simplified if all calculations are based upon the actual total value of the ampere-turns per pole of the main exciting winding and an equivalent value of the armature M.M.F. This equivalent value of the armature ampere-turns is given by the value of the ampere-conductors per pole multiplied by the constant $K_r = 0·25\sqrt{2}\,\frac{\beta}{\beta'}\cdot\frac{\sin\beta}{\sin\beta'}$. Values of this constant are given in Table 2a for the case of full-pitch armature windings, and the method of dealing with fractional-pitch and other more abnormal windings is discussed.

So far as other methods of calculating the armature M.M.F. are concerned, this investigation shows that by dealing with the mean values of the actual M.M.F. wave-forms for polyphase machines, the result obtained does not differ appreciably from the mean value obtained by considering only the fundamental harmonics. In the case of the main exciting M.M.F., however, by dealing with the mean value of the actual wave, an error is introduced for all cases in which the half spread of the winding differs from one radian. The magnitude of the error obtained by the method of dealing with the mean values of the M.M.F. waves is thus confined to the estimation of the value of the main M.M.F. In cases where great accuracy is required, such as in the determination of the reactance of the armature winding from the measured open-circuit and short-circuit characteristics, the error due to the employment of such a method may in certain cases be much greater than is desirable.

With single-phase machines a further error may be introduced in cases where the spread of the armature winding differs appreciably from one radian; on the other hand, the error in the estimation of the armature M.M.F. may tend to neutralize that in the estimation of the main M.M.F., Table 3 indicating the error which may arise from this source.

Owing to circumstances mentioned earlier in the paper, it is possible that reference has not been made to all the work of others who may have contributed to the literature of subjects bearing upon the present paper. Should this be the case, the author begs to express his regret at any such omission.

APPENDIX.

I. The Harmonic Analysis of Rectilinear Wave-forms.

For a wave-form which is symmetrical about the 90° axis and contains no even harmonics, the corresponding Fourier series is:

$$y = Y_1 \sin\theta + Y_3 \sin 3\theta + \ldots + Y_n \sin n\theta + \ldots .$$

The amplitude of the nth harmonic is given by

$$Y_n = \frac{2}{\pi}\int_0^{\pi} y \sin n\theta\, d\theta$$

The elemental wave-form, from which most of the actual M.M.F. waves met with in practice can be built up, is of the trapezium type shown in Fig. 14.

This wave-form consists of two parts: (1) The inclined portion from θ_1 to θ_2, for which

$$y = k(\theta - \theta_1), \text{ where } k = X/(\theta_2 - \theta_1)$$

and (2) the rectangular portion from θ_2 to $\pi/2$, for which portion

$$y = X = k(\theta_2 - \theta_1)$$

Hence, for the trapezium wave shown in Fig. 14, the amplitude of the nth harmonic is :

$$A_n = \frac{2}{\pi} \times 2 \left[\int_{\theta_1}^{\theta_2} k(\theta - \theta_1) \sin n\theta \, d\theta + \int_{\theta_2}^{\tau/2} k(\theta_2 - \theta_1) \sin n\theta \, d\theta \right]$$

$$= \frac{4}{\pi} \times \frac{k}{n^2} \left(\sin n\theta_2 - \sin n\theta_1 \right)$$

$$= \frac{4}{\pi} \times \frac{X}{(\theta_2 - \theta_1)} \times \frac{1}{n^2} \left(\sin n\theta_2 - \sin n\theta_1 \right)$$

For certain cases it is more convenient to express the amplitude of the harmonic in the form :

$$A_n = \frac{4}{\pi} \times \frac{X}{(\theta_2 - \theta_1)} \times \frac{1}{n^2} \left\{ 2 \cos \frac{n(\theta_2 + \theta_1)}{2} \sin \frac{n(\theta_2 - \theta_1)}{2} \right\}$$

From the above equations the amplitude of the nth harmonic for any normal rectilinear wave-form which is symmetrical about the 90° axis can readily be determined by resolving the actual wave into a number of component trapezium waves. Rectangular and triangular waves may be treated as being the limiting cases of the trapezium. Thus, in Fig. 15 the wave-form shown may be resolved into the three component waves indicated.

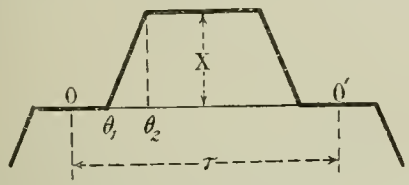

Fig. 14.—General case of trapezium wave-form.

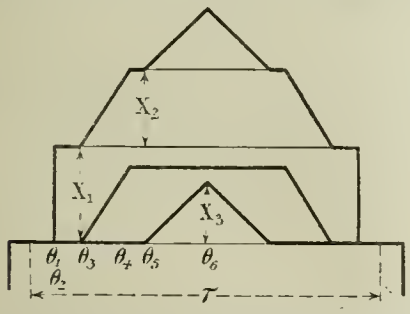

Fig. 15.—Showing the resolution of a rectilinear wave-form into its component wave-shapes.

The amplitude of the nth harmonic in the actual wave is obtained from the sum of the amplitudes of that particular harmonic in the various component waves.

Hence, for the general case as in Fig. 16 :

$$A_n = \frac{4}{\pi} \times \frac{1}{n^2} \left\{ \frac{2X_1}{\theta_2 - \theta_1} \cos \frac{n(\theta_2 + \theta_1)}{2} \sin \frac{n(\theta_2 - \theta_1)}{2} + \frac{2X_2}{(\theta_4 - \theta_3)} \cos \frac{n(\theta_4 + \theta_3)}{2} \sin \frac{n(\theta_4 - \theta_3)}{2} \cdots \right\}$$

In this expression, X_1, X_2, etc., and θ_1, θ_2, etc., have the values indicated in Fig. 16.

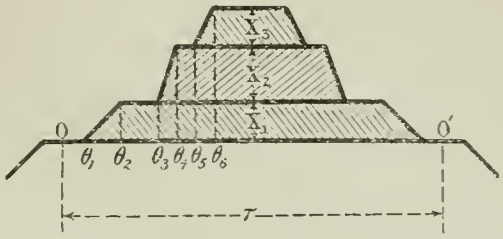

Fig. 16.—Irregular stepped wave-form resolved into its component trapezium waves.

Thus the amplitude of any of the harmonics can be determined for any rectilinear wave containing no even harmonics and symmetrical about the 90° axis.

II. Stepped Rectilinear Waves.

With a distributed winding the M.M.F. wave is of this type.

(*a*) *General case.*—This corresponds to irregular distribution of the winding. For this case no simplification of the above formula is possible, and the value of the fundamental harmonic in the wave-form must be obtained as indicated above.

(*b*) *Regular slotting, but varying M.M.F. per slot.*

Let 2ψ = the slot width expressed in electrical radians, and 2γ = the slot-pitch similarly expressed.

Then $\psi = (\theta_2 - \theta_1)/2 = (\theta_4 - \theta_3)/2 = \text{etc.}$,

and $(\theta_2 + \theta_1)/2 = \gamma$; $(\theta_4 + \theta_3)/2 = 3\gamma$; $(\theta_6 + \theta_5)/2 = 5\gamma$, etc.

and the amplitude of the nth harmonic becomes

$$A_n = \frac{4}{\pi} \times \frac{1}{n^2} \times \frac{\sin n\psi}{\psi} \left\{ X_1 \cos n\gamma + X_2 \cos 3n\gamma + \cdots + X_{s/2} \cos (s_c - 1) n\gamma \right\}$$

and

$$A_1 = \frac{4}{\pi} \times \frac{\sin \psi}{\psi} \left\{ X_1 \cos \gamma + X_2 \cos 3\gamma + \cdots + X_{s/2} \cos (s_c - 1)\gamma \right\}$$

This enables the case of a machine in which some of the slots contain a reduced number of conductors to be dealt with exactly.

(*c*) *Irregular slotting.*—With solid rotors, irregular slotting may occasionally be used.

Let $\frac{\theta_2 + \theta_1}{2} = \gamma_1$, $\frac{\theta_4 + \theta_3}{2} = \gamma_2$, $\frac{\theta_6 + \theta_5}{2} = \gamma_3$, etc.

Then for the particular case when the M.M.F. per slot is constant :

$$A_1 = \frac{4X_1}{\pi} \times \frac{\sin \psi}{\psi} \left\{ \cos \gamma_1 + \cos \gamma_2 + \cdots + \cos \gamma_{s_c/2} \right\}$$

III. Rectilinear Waves with Regular Steps.

For this case, the one normally met with in practice,

$$X_1 = X_2 = X_3 = X_4, \text{ etc.}, = 2X/s_c$$

γ and ψ have the values indicated above, and $s_c\gamma = \beta_c$.

Thus the amplitude of the nth harmonic becomes

$$A_n = \frac{4}{\pi}\frac{X_1}{\psi}\frac{\sin n\psi}{n^2}\left\{\cos n\gamma + \cos 3n\gamma + \ldots \cos(s-1)n\gamma\right\}$$

$$= \frac{4}{\pi}\frac{X}{\psi}\frac{1}{n^2}\frac{\sin n\psi}{\sin n\gamma}$$

and $A_1 = \frac{4}{\pi}\frac{X}{\psi}\frac{\sin\psi}{\sin\gamma}$.

The general case of a rectilinear wave having regular steps is thus completely solved. For certain special cases the expressions given may be further simplified.

(*a*) *Uniform rectangular steps* (see Fig. 3*c*).—For this case $\delta = 0$, and hence

$$A_n = \frac{4}{\pi}\frac{X}{\psi}\frac{1}{n^2}\frac{\sin n\beta_e}{\sin n\gamma}$$

and $$A_1 = \frac{4}{\pi}\frac{X}{\psi}\frac{\sin\beta_e}{\sin\gamma}$$

For the higher harmonics of the orders $(2Q \pm 1)$, the amplitudes become

$$A_{(2Q\pm1)} = \frac{4}{\pi}\frac{X}{\psi}\frac{1}{(2Q_e\pm1)^2}\frac{\sin(2Q_e\pm1)\beta_e}{\sin(2Q_e\pm1)\gamma}$$

$$= \frac{4}{\pi}\frac{X}{\psi}\frac{\sin\beta_e}{(2Q_e\pm1)\sin\gamma}$$

$$= \pm\frac{4}{\pi}\frac{X}{\psi}\frac{\sin\beta_e}{\beta_e}\frac{1}{(2Q_e\pm1)}$$

Expressed in terms of the fundamental harmonic of the corresponding trapezium wave (Fig. 1), the values of the above harmonics become

$$A_1 = \frac{\beta_e}{\psi_e\sin\gamma}\ 100, \text{ per cent}$$

$$A_{(2Q-1)} = \frac{1}{(2Q_e-1)}\ 100, \text{ per cent}$$

and $$A_{(2Q+1)} = \frac{1}{(2Q_e+1)}\ 100, \text{ per cent}$$

(*b*) *Uniform steps as in Fig. 3d.*—For this case the slot width is equal to the tooth width, and therefore $\gamma = 2\psi$, and $\beta = 2\psi_e$. Hence

$$A_n = \frac{4}{\pi}\frac{X}{\psi}\frac{1}{n^2}\frac{\sin n\psi}{\psi_e}\frac{\sin n\beta}{\sin 2n\psi}$$

$$= \frac{4}{\pi}\frac{X}{\psi}\frac{1}{n^2}\frac{\sin n\beta_e}{\beta_e}\frac{1}{\cos n\psi}$$

and $$A_1 = \frac{4}{\pi}\frac{X}{\psi}\frac{\sin\beta_e}{\beta_e}\frac{1}{\cos\psi}$$

$$A_{(2Q\pm1)} = \frac{4}{\pi}\frac{X}{\psi}\frac{1}{(2Q_e\pm1)^2}\frac{\sin(2Q_e\pm1)\beta_e}{\beta_e}\frac{1}{\cos(2Q_e\pm1)\psi}$$

$$= -\frac{4}{\pi}\frac{X}{\psi}\frac{1}{(2Q_e\pm1)^2}\frac{\sin\beta_e}{\beta_e}\frac{1}{\sin\psi}$$

$$= -\frac{4}{\pi}\frac{X}{\psi}\frac{\sin\beta_e}{\beta_e}\frac{4Q_e}{\pi(2Q_e\pm1)^2}$$

In terms of the fundamental harmonic of the corresponding trapezium wave, the values of the above harmonics become

$$A_1 = (1-\cos\psi)\ 100 \div (1+\psi^2/2)\ 100, \text{ per cent}$$

$$A_{(2Q-1)} = \frac{1}{\pi(Q-1)}\ 100, \text{ per cent}$$

and $$A_{(2Q+1)} = \frac{1}{\pi(Q+1)}\ 100, \text{ per cent}$$

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A PRACTICAL METHOD OF HARMONIC ANALYSIS.*

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SUMMARY.

Object.—To provide a self-explanatory schedule for routine work.

Method.—Sums and differences of observations are taken (as in the late Professor S. P. Thompson's method and others).

A sufficient number of values are solved in general terms, so that working an example is reduced to filling in values in known equations. This work is expedited very materially by means of the schedule. Nothing but a slide rule is necessary, and the actual calculations can be carried out by persons with no great knowledge of mathematics.

Results.—An example has been worked out up to the 17th harmonic in 50 minutes, thus comparing favourably in this respect with other methods. Furthermore, the results are given in the form $E \sin(\theta + \alpha)$, which is more useful than $E_A \sin\theta + E_B \cos\theta$.

In cases where harmonics higher than the 17th are present in appreciable magnitude, an increased accuracy in the analysis is obtained for a given number of ordinates.

Most of the methods of analysing periodic wave-forms at present in use are rather tedious to carry out and necessitate a good deal of time being spent in the evaluation of the various constants. The present paper is an effort to expedite calculations of this kind and to provide a ready method, by means of a simple series of equations, for the analysis of periodic wave-forms.

In common with other methods, the labour involved in the calculations increases very rapidly as the number of harmonics, for which it is desired to solve, increases, and in consequence of this the analysis set out below has only been carried out to the 17th harmonic. In practice it is rarely required to determine harmonics of a higher order than this. The special case of problems due to tooth-ripples, however, where higher harmonics are often met with, calls for a rather different procedure which is explained later.

The method adopted below is carried out on somewhat similar lines to that described by the late Professor S. P. Thompson,* and consists of taking sums and differences of certain chosen ordinates, these being, in the present case, spaced equi-distantly on either side of an arbitrarily chosen zero. The algebraic sum of each pair of readings is equal to a series of terms of the type $2 E \sin\alpha \cos\theta$. Here, θ is equal to some known angle which is determined by the position of the ordinates chosen, and E and α are constants depending upon the composition of the wave. In a similar manner the algebraic differences of the same pairs of ordinates give rise to a series of terms of the type $2 E \cos\alpha \sin\theta$, the symbols having the same meaning as before. When a sufficient number of such equations is obtained, they can be solved in terms of the quantities $E \sin\alpha$ and $E \cos\alpha$.

In solving up to the 17th harmonic there are 18 unknown quantities to be determined, viz. the amplitudes and phase angles of the fundamental and the eight harmonics. Thus 18 simultaneous equations are required, the necessary data being obtained from 18 chosen ordinates. In order to minimize errors due to the incorrect drawing of the curve, these ordinates are chosen at equal distances apart, viz. at 5°, 15°, 25° . . . 165° and 175° from the point selected as zero. The values of these various ordinates will be represented by V_5, V_{15}, V_{25} . . . V_{165} and V_{175}. Any point on the wave may be chosen as the zero, but usually it is convenient to select a point where the wave crosses the axis. In all probability this will not coincide with the zero value of the fundamental, but, if so desired, on the completion of the analysis the expression for the

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

* *Electrician*, 1905, vol. 55, p. 79; and *Proceedings of the Physical Society*, 1911, vol. 23, p. 334.

wave can be re-stated so as to bring about this coincidence.

Let the wave be represented by the expression

$$V_\theta = E_1 \sin(\theta + a_1) + E_3 \sin(3\theta + a_3) + \ldots + E_{17} \sin(17\theta + a_{17})$$

where E_1, E_3 ... E_{17} represent the amplitudes of the fundamental and the respective harmonics; $a_1, a_3 \ldots a_{17}$ the phase angles with respect to the point chosen as the zero and from which values of θ are measured; and V_θ the value of the ordinate at the angle θ. Care should be taken to avoid confusion owing to the double sense in which the suffixes are used. Then

$$V_{85} = E_1 \sin(85° + a_1) + E_3 \sin(255° + a_3) + E_5 \sin(425° + a_5) + \ldots + E_{17} \sin(1445° + a_{17})$$

and

$$-V_{95} = V_{-85} = E_1 \sin(-85° + a_1) + E_3 \sin(-255° + a_3) + E_5 \sin(-425° + a_5) + \ldots + E_{17} \sin(-1445° + a_{17})$$

Therefore

$$V_{85} - V_{95} = V_{85} + V_{-85} = 2E_1 \sin a_1 \cos 85° + 2E_3 \sin a_3 \cos 255° + 2E_5 \sin a_5 \cos 65° + \ldots + 2E_{17} \sin a_{17} \cos 5°$$

Similarly

$$V_{75} - V_{105} = V_{75} + V_{-75} = 2E_1 \sin a_1 \cos 75° + 2E_3 \sin a_3 \cos 225° + 2E_5 \sin a_5 \cos 15° + \ldots + 2E_{17} \sin a_{17} \cos 195°$$

Other readings are taken every 10° until V_5 and V_{175} are reached. Then the resulting nine simultaneous equations are solved, thus obtaining $E_1 \sin a_1$, $E_3 \sin a_3$, etc., in terms of $(V_{85} - V_{95})$, $(V_{75} - V_{105})$, ... $(V_5 - V_{175})$.

A second series of calculations must now be made as follows:—

$$V_{85} - V_{95} = V_{85} - V_{-85} = 2E_1 \cos a_1 \sin 85° + 2E_3 \cos a_3 \sin 225° + 2E_5 \cos a_5 \sin 65° + \ldots + 2E_{17} \cos a_{17} \sin 5°$$

$$V_{75} + V_{105} = V_{75} - V_{-75} = 2E_1 \cos a_1 \sin 75° + 2E_3 \cos a_3 \sin 225° + 2E_5 \cos a_5 \sin 15° + \ldots + 2E_{17} \cos a_{17} \sin 195°$$

In this way another nine simultaneous equations are obtained and $E_1 \cos a_1$, $E_3 \cos a_3$, etc., are evaluated in terms of $(V_{85} + V_{95})$, $(V_{75} + V_{105})$, ... $(V_5 + V_{175})$.

The complete solutions of these 18 equations are set out in full in Table 1.

Then $$E_1 = \sqrt{(E_1 \sin a_1)^2 + (E_1 \cos a_1)^2}$$

and $$a_1 = \tan^{-1}\left[\frac{E_1 \sin a_1}{E_1 \cos a_1}\right]$$

and similarly for the various harmonics. Care must be taken to observe the signs of $E \sin a$ and $E \cos a$, as these determine the quadrant in which a is situated.

The initial labour in solving the above equations is considerable, but this having been done, the problem resolves itself into a number of multiplications of the various chosen ordinates by certain known constants.

TABLE 1.

$E_1 \sin a_1 = +0{\cdot}009_7 A_1 + 0{\cdot}028_7 B_1 + 0{\cdot}046_9 C_1 + 0{\cdot}063_7 D_1 + 0{\cdot}078_5 F_1 + 0{\cdot}091_0 G_1 + 0{\cdot}100_7 H_1 + 0{\cdot}107_3 L_1 + 0{\cdot}110_7 M_1$

$E_1 \cos a_1 = +0{\cdot}110_7 A_2 + 0{\cdot}107_3 B_2 + 0{\cdot}100_7 C_2 + 0{\cdot}091_0 D_2 + 0{\cdot}078_5 F_2 + 0{\cdot}063_7 G_2 + 0{\cdot}046_9 H_2 + 0{\cdot}028_7 L_2 + 0{\cdot}009_7 M_2$

$E_3 \sin a_3 = -0{\cdot}028_7 A_1 - 0{\cdot}078_5 B_1 - 0{\cdot}107_3 C_1 - 0{\cdot}107_3 D_1 - 0{\cdot}078_5 F_1 - 0{\cdot}028_7 G_1 + 0{\cdot}028_7 H_1 + 0{\cdot}078_5 L_1 + 0{\cdot}107_3 M_1$

$E_3 \cos a_3 = -0{\cdot}107_3 A_2 - 0{\cdot}078_5 B_2 - 0{\cdot}028_7 C_2 + 0{\cdot}028_7 D_2 + 0{\cdot}078_5 F_2 + 0{\cdot}107_3 G_2 + 0{\cdot}107_3 H_2 + 0{\cdot}078_5 L_2 + 0{\cdot}028_7 M_2$

$E_5 \sin a_5 = +0{\cdot}046_9 A_1 + 0{\cdot}107_3 B_1 + 0{\cdot}091_0 C_1 + 0{\cdot}009_7 D_1 - 0{\cdot}078_5 F_1 - 0{\cdot}110_7 G_1 - 0{\cdot}063_7 H_1 + 0{\cdot}028_7 L_1 + 0{\cdot}100_7 M_1$

$E_5 \cos a_5 = +0{\cdot}100_7 A_2 + 0{\cdot}028_7 B_2 - 0{\cdot}063_7 C_2 - 0{\cdot}110_7 D_2 - 0{\cdot}078_5 F_2 + 0{\cdot}009_7 G_2 + 0{\cdot}091_0 H_2 + 0{\cdot}107_3 L_2 + 0{\cdot}046_9 M_2$

$E_7 \sin a_7 = -0{\cdot}063_7 A_1 - 0{\cdot}107_3 B_1 - 0{\cdot}009_7 C_1 + 0{\cdot}100_7 D_1 + 0{\cdot}078_5 F_1 - 0{\cdot}046_9 G_1 - 0{\cdot}110_7 H_1 - 0{\cdot}028_7 L_1 + 0{\cdot}091_0 M_1$

$E_7 \cos a_7 = -0{\cdot}091_0 A_2 + 0{\cdot}028_7 B_2 + 0{\cdot}110_7 C_2 + 0{\cdot}046_9 D_2 - 0{\cdot}078_5 F_2 - 0{\cdot}100_7 G_2 + 0{\cdot}009_7 H_2 + 0{\cdot}107_3 L_2 - 0{\cdot}063_7 M_2$

$E_9 \sin a_9 = +0{\cdot}078_5 A_1 + 0{\cdot}078_5 B_1 - 0{\cdot}078_5 C_1 - 0{\cdot}078_5 D_1 + 0{\cdot}078_5 F_1 + 0{\cdot}078_5 G_1 - 0{\cdot}078_5 H_1 - 0{\cdot}078_5 L_1 + 0{\cdot}078_5 M_1$

$E_9 \cos a_9 = +0{\cdot}078_5 A_2 - 0{\cdot}078_5 B_2 - 0{\cdot}078_5 C_2 + 0{\cdot}078_5 D_2 + 0{\cdot}078_5 F_2 - 0{\cdot}078_5 G_2 - 0{\cdot}078_5 H_2 + 0{\cdot}078_5 L_2 + 0{\cdot}078_5 M_2$

$E_{11} \sin a_{11} = -0{\cdot}091_0 A_1 - 0{\cdot}028_7 B_1 + 0{\cdot}110_7 C_1 + 0{\cdot}046_9 D_1 - 0{\cdot}078_5 F_1 + 0{\cdot}100_7 G_1 + 0{\cdot}009_7 H_1 - 0{\cdot}107_3 L_1 + 0{\cdot}063_7 M_1$

$E_{11} \cos a_{11} = -0{\cdot}063_7 A_2 - 0{\cdot}107_3 B_2 - 0{\cdot}009_7 C_2 - 0{\cdot}100_7 D_2 + 0{\cdot}078_5 F_2 + 0{\cdot}046_9 G_2 - 0{\cdot}110_7 H_2 + 0{\cdot}028_7 L_2 + 0{\cdot}091_0 M_2$

$E_{13} \sin a_{13} = +0{\cdot}100_7 A_1 - 0{\cdot}028_7 B_1 - 0{\cdot}063_7 C_1 + 0{\cdot}110_7 D_1 - 0{\cdot}078_5 F_1 - 0{\cdot}009_7 G_1 + 0{\cdot}091_0 H_1 - 0{\cdot}107_3 L_1 + 0{\cdot}046_9 M_1$

$E_{13} \cos a_{13} = +0{\cdot}046_9 A_2 - 0{\cdot}107_3 B_2 + 0{\cdot}091_0 C_2 - 0{\cdot}009_7 D_2 - 0{\cdot}078_5 F_2 + 0{\cdot}110_7 G_2 - 0{\cdot}063_7 H_2 - 0{\cdot}028_7 L_2 + 0{\cdot}100_7 M_2$

$E_{15} \sin a_{15} = -0{\cdot}107_3 A_1 + 0{\cdot}078_5 B_1 - 0{\cdot}028_7 C_1 - 0{\cdot}028_7 D_1 + 0{\cdot}078_5 F_1 - 0{\cdot}107_3 G_1 + 0{\cdot}107_3 H_1 - 0{\cdot}078_5 L_1 + 0{\cdot}028_7 M_1$

$E_{15} \cos a_{15} = -0{\cdot}028_7 A_2 - 0{\cdot}078_5 B_2 - 0{\cdot}107_3 C_2 + 0{\cdot}107_3 D_2 - 0{\cdot}078_5 F_2 + 0{\cdot}028_7 G_2 + 0{\cdot}028_7 H_2 - 0{\cdot}078_5 L_2 + 0{\cdot}107_3 M_2$

$E_{17} \sin a_{17} = +0{\cdot}110_7 A_1 - 0{\cdot}107_3 B_1 + 0{\cdot}100_7 C_1 - 0{\cdot}091_0 D_1 + 0{\cdot}078_5 F_1 - 0{\cdot}063_7 G_1 + 0{\cdot}046_9 H_1 - 0{\cdot}028_7 L_1 + 0{\cdot}009_7 M_1$

$E_{17} \cos a_{17} = -0{\cdot}009_7 A_2 + 0{\cdot}028_7 B_2 - 0{\cdot}046_9 C_2 + 0{\cdot}063_7 D_2 - 0{\cdot}078_5 F_2 + 0{\cdot}091_0 G_2 - 0{\cdot}100_7 H_2 + 0{\cdot}107_3 L_2 - 0{\cdot}110_7 M_2$

Note.—$A_1 = (V_{85} - V_{95})$, $B_1 = (V_{75} - V_{105})$, $C_1 = (V_{65} - V_{115})$, $D_1 = (V_{55} - V_{125})$; $F_1 = (V_{45} - V_{135})$, $G_1 = (V_{35} - V_{145})$; $A_2 = (V_{85} + V_{95})$, $B_2 = (V_{75} + V_{105})$, $C_2 = (V_{65} + V_{115})$, $D_2 = (V_{55} + V_{125})$, $F_2 = (V_{45} + V_{135})$, $G_2 = (V_{35} + V_{145})$;

$H_1 = (V_{25} - V_{155})$, $L_1 = (V_{15} - V_{165})$, $M_1 = (V_5 - V_{175})$.

$H_2 = (V_{25} + V_{155})$, $L_2 = (V_{15} + V_{165})$, $M_2 = (V_5 + V_{175})$.

The analysis once completed in this manner subsequent examples become a matter of simple arithmetic.

In order to facilitate the actual calculations still further, a schedule has been drawn up as shown in Table 2. This schedule is self-explanatory; in fact, it is not even necessary to be familiar with the underlying principles in order to work out an example.

In cases where it is not desired to carry out the analysis as far as this, the same set of constants may, of course, be used. It would be possible to use a smaller number of ordinates for which a new set of constants would be required; but by using those already determined the advantage of the increased number of points is obtained with corresponding increased accuracy. For, by using the constants given in the table, the effect of all the harmonics up to the 17th is allowed for, whereas if another series of equations were evaluated to solve, say, up to the 11th harmonic, then all the undetermined harmonics between the 11th and the 17th would tend to produce errors in those which had been determined. It should be noted also that the fundamental of any particular wave may be determined by itself without carrying out the analysis any further.

The coefficients given in the table are correct to three figures in an example containing harmonics not higher than the 17th. When higher harmonics than this are introduced their effects are averaged out amongst the lower ones, those of higher frequency being most affected. In the majority of cases, however, harmonics of a higher frequency than the 17th may be neglected. If a larger number of ordinates is chosen, with a new set of constants, increased labour is entailed, resulting in increased accuracy in those cases where harmonics higher than the 17th are present in appreciable magnitude. A method of minimizing the effect of the higher harmonics is to re-analyse the wave, choosing a second arbitrary zero, say 45° away from the first, the average of the two analyses then being taken. The present method compares favourably with other approximate solutions, even taking a single analysis, since the errors introduced by using a limited number of ordinates are neutralized to a certain extent by the diversity of the coefficients employed. Take, for example, the analysis of (*a*) a rectangular, and (*b*) a triangular wave. These are very severe tests on account of the fact that each of these waves contains an infinite number of harmonics, those immediately following the 17th being almost as large as those immediately preceding it. The magnitudes of the harmonics have been worked out below by the series

$$e = \frac{4E}{\pi}\left[\frac{\sin \omega t}{1} + \frac{\sin 3\omega t}{3} + \frac{\sin 5\omega t}{5} + \frac{\sin 7\omega t}{7} + \cdots\right] \text{ Rectangular wave}$$

and

$$e = \frac{8E}{\pi^2}\left[\frac{\sin \omega t}{1} - \frac{\sin 3\omega t}{9} + \frac{\sin 5\omega t}{25} - \frac{\sin 7\omega t}{49} + \cdots\right] \text{ Triangular wave}$$

and these have been compared with the analyses by Thompson's and the author's methods, using the same number of ordinates. It is seen that a nearer approximation to the correct values of the harmonics, and also the R.M.S. values, is obtained by the present method.

Analysis of Rectangular Wave-form.

Max. Value = 100, *R.M.S. Value* = 100.

Coefficients	True Values by Series	Author's Method	Thompson's Method
E_1	127·33	127·4	127·0
E_3	42·44	42·9	41·5
E_5	25·47	26·3	23·8
E_7	18·19	19·4	15·9
E_9	14·15	15·7	11·1
E_{11}	11·58	13·5	7·8
E_{13}	9·79	12·3	5·2
E_{15}	8·49	11·5	3·0
E_{17}	7·49	11·2	1·0
E_{19}	6·70	—	—
E_{21}	6·06	—	—
E_{23}	5·54	—	—
E_{25}	5·09	—	—
R.M.S. value up to 17th harmonic	98·9	99·95	97·2

Analysis of Triangular Wave-form.

Max. Value = 100, *R.M.S. Value* = $100/\sqrt{3} = 57{\cdot}7$.

Coefficients	True Values by Series	Author's Method	Thompson's Method
E_1	81·06	80·9	81·3
E_3	— 9·01	— 8·9	— 9·2
E_5	3·24	3·2	3·45
E_7	— 1·65	— 1·5	— 1·9
E_9	1·00	0·9	1·2
E_{11}	— 0·67	— 0·6	— 0·9
E_{13}	·0·48	0·3	0·75
E_{15}	— 0·36	— 0·2	— 0·65
E_{17}	0·28	0·1	0·6
E_{19}	— 0·22	—	—
E_{21}	0·18	—	—
E_{23}	— 0·15	—	—
E_{25}	0·13	—	—
R.M.S. value up to 17th harmonic	57·7	57·6	57·9

The present method does not, of course, give such accurate results as some of the more lengthy methods which have, from time to time, been advanced,* but gives results sufficiently accurate for the majority of practical cases in alternating-current working. In any case, methods involving the erection of a number of ordinates, at least equal to 12 times the number of the harmonic,† are not generally applicable to oscillographic records, since such methods require 204 equidistant ordinates per period of the fundamental for the determination of the 17th harmonic.

* See Russell's "Alternating Currents," vol. 2, 2nd ed. chap. 3.
† *Ibid.*

TABLE 2

	1	2	3 = 1 − 2 Difference	$I_1 \sin a_1$ terms 4 Constants	5 = 3 + 4 +	5 = 3 + 4 −	$I_3 \sin a_3$ terms 6 Constants	7 = 3 + 6 +	7 = 3 + 6 −	$I_5 \sin a_5$ terms 8 Constants	9 = 3 + 8 +	9 = 3 + 8 −	$I_7 \sin a_7$ terms 10 Constants	11 = 3 + 10 +	11 = 3 + 10 −
Differences	V_{25}	V_{23}		$-0{\cdot}000_7$			$-0{\cdot}028_7$			$+0{\cdot}040_9$			$-0{\cdot}063_7$		
	V_{27}	V_{25}		$+0{\cdot}028_7$			$-0{\cdot}078_5$			$+0{\cdot}107_3$			$-0{\cdot}107_3$		
	V_{29}	V_{27}		$0{\cdot}040_9$			$-0{\cdot}107_3$			$+0{\cdot}091_0$			$-0{\cdot}009_7$		
	V_{31}	V_{29}		$+0{\cdot}063_7$			$-0{\cdot}107_3$			$+0{\cdot}009_7$			$+0{\cdot}100_7$		
	V_{33}	V_{31}		$0{\cdot}078_5$			$-0{\cdot}078_5$			$-0{\cdot}078_5$			$+0{\cdot}078_5$		
	V_{35}	V_{33}		$+0{\cdot}091_0$			$-0{\cdot}028_7$			$-0{\cdot}110_7$			$-0{\cdot}040_9$		
	V_{37}	V_{35}		$0{\cdot}100_7$			$+0{\cdot}028_7$			$0{\cdot}063_7$			$-0{\cdot}110_7$		
	V_{39}	V_{37}		$0{\cdot}107_3$			$+0{\cdot}078_5$			$+0{\cdot}028_7$			$-0{\cdot}028_7$		
	V_{41}	V_{39}		$+0{\cdot}110_7$			$+0{\cdot}107_3$			$+0{\cdot}100_7$			$+0{\cdot}091_0$		
				Sum of − terms			Sum of − terms			Sum of + terms			Sum of + terms		
				Sum of + terms			Sum of + terms			Sum of − terms			Sum of − terms		
			V	Sum total = $E_1 \sin a_1$			Sum total = $E_3 \sin a_3$			Sum total = $E_5 \sin a_5$			Sum total = $E_7 \sin a_7$		

	1	2	22 = 1 + 2 Sum	$E_1 \cos a_1$ terms 23 Constants	24 = 22 + 23 +	24 = 22 + 23 −	$E_3 \cos a_3$ terms 25 Constants	26 = 22 + 25 +	26 = 22 + 25 −	$E_5 \cos a_5$ terms 27 Constants	28 = 22 + 27 +	28 = 22 + 27 −	$E_7 \cos a_7$ terms 29 Constants	30 = 22 + 29 +	30 = 22 + 29 −
Sums	V_{25}	V_{23}		$-0{\cdot}110_7$			$-0{\cdot}107_3$			$+0{\cdot}100_7$			$-0{\cdot}091_0$		
	V_{27}	V_{25}		$-0{\cdot}107_3$			$-0{\cdot}078_5$			$+0{\cdot}028_7$			$+0{\cdot}028_7$		
	V_{29}	V_{27}		$+0{\cdot}100_7$			$-0{\cdot}028_7$			$0{\cdot}063_7$			$+0{\cdot}110_7$		
	V_{31}	V_{29}		$+0{\cdot}091_0$			$+0{\cdot}028_7$			$-0{\cdot}110_7$			$+0{\cdot}040_9$		
	V_{33}	V_{31}		$+0{\cdot}078_5$			$-0{\cdot}078_5$			$-0{\cdot}078_5$			$-0{\cdot}078_5$		
	V_{35}	V_{33}		$+0{\cdot}063_7$			$+0{\cdot}107_3$			$+0{\cdot}009_7$			$-0{\cdot}100_7$		
	V_{37}	V_{35}		$+0{\cdot}040_9$			$+0{\cdot}107_3$			$+0{\cdot}001_0$			$+0{\cdot}009_7$		
	V_{39}	V_{37}		$+0{\cdot}028_7$			$+0{\cdot}078_5$			$+0{\cdot}107_3$			$+0{\cdot}107_3$		
	V_{41}	V_{39}		$+0{\cdot}000_7$			$+0{\cdot}028_7$			$+0{\cdot}040_9$			$+0{\cdot}063_7$		
				Sum of + terms			Sum of + terms			Sum of + terms			Sum of + terms		
				Sum of − terms			Sum of − terms			Sum of − terms			Sum of − terms		
			B	Sum total = $E_1 \cos a_1$			Sum total = $E_3 \cos a_3$			Sum total = $E_5 \cos a_5$			Sum total = $E_7 \cos a_7$		
			A^2	$(E_1 \sin a_1)^2$			$(E_3 \sin a_3)^2$			$(E_5 \sin a_5)^2$			$(E_7 \sin a_7)^2$		
			B^2	$(E_1 \cos a_1)^2$			$(E_3 \cos a_3)^2$			$(E_5 \cos a_5)^2$			$(E_7 \cos a_7)^2$		
			$A^2 + B^2$	E_1^2			E_3^2			E_5^2			E_7^2		
			$\sqrt{(A^2 + B^2)}$	E_1			E_3			E_5			E_7		
			A	$E_1 \sin a_1$			$E_3 \sin a_3$			$E_5 \sin a_5$			$E_7 \sin a_7$		
			B	$E_1 \cos a_1$			$E_3 \cos a_3$			$E_5 \cos a_5$			$E_7 \cos a_7$		
			$\tan^{-1}\left(\frac{A}{B}\right)$	a_1			a_3			a_5			a_7		

$V = \sin(\theta + \quad^\circ) + \sin(3\theta + \quad^\circ) + \sin(5\theta + \quad^\circ) + \sin(7\theta + \quad^\circ)$

TABLE 2—*continued.*

$E_9 \sin a_9$ terms			$E_{11} \sin a_{11}$ terms			$E_{13} \sin a_{13}$ terms			$E_{15} \sin a_{15}$ terms			$E_{17} \sin a_{17}$ terms		
12	13=3×12		14	15=3×14		16	17=3×16		18	19=3×18		20	21=3×20	
Constants	+	−	Constants	+	−	Constants	+	−	Constants	+	−	Constants	+	−
+1			$-0\cdot091_0$			$+0\cdot100_7$			$-0\cdot107_3$			$+0\cdot110_7$		
+1			$-0\cdot028_7$			$-0\cdot028_7$			$+0\cdot078_5$			$-0\cdot107_3$		
−1			$+0\cdot110_7$			$-0\cdot063_7$			$-0\cdot028_7$			$+0\cdot100_7$		
−1			$-0\cdot046_9$			$+0\cdot110_7$			$-0\cdot028_7$			$-0\cdot091_0$		
−1			$-0\cdot078_5$			$-0\cdot078_5$			$+0\cdot078_5$			$+0\cdot078_5$		
+1			$+0\cdot100_7$			$-0\cdot009_7$			$-0\cdot107_3$			$-0\cdot063_7$		
−1			$+0\cdot009_7$			$+0\cdot091_0$			$+0\cdot107_3$			$+0\cdot046_9$		
−1			$-0\cdot107_3$			$-0\cdot107_3$			$-0\cdot078_5$			$-0\cdot028_7$		
+1			$+0\cdot063_7$			$+0\cdot046_9$			$+0\cdot028_7$			$+0\cdot009_7$		
Sum of +terms			Sum of +terms			Sum of +terms			Sum of +terms			Sum of −terms		
Sum of −terms			Sum of −terms			Sum of −terms			Sum of −terms			Sum of −terms		
Sum total														
$0\cdot078_5\times$ (Sum total) = $E_9 \sin a_9$			Sum total = $E_{11} \sin a_{11}$			Sum total = $E_{13} \sin a_{13}$			Sum total = $E_{15} \sin a_{15}$			Sum total = $E_{17} \sin a_{17}$		

$E_9 \cos a_9$ terms			$E_{11} \cos a_{11}$ terms			$E_{13} \cos a_{13}$ terms			$E_{15} \cos a_{15}$ terms			$E_{17} \cos a_{17}$ terms		
31	32=22×31		33	34=22×33		35	36=22×35		37	38=22×37		39	40=22×39	
Constants	+	−	Constants	+	−	Constants	+	−	Constants	+	−	Constants	+	−
+1			$-0\cdot063_7$			$+0\cdot046_9$			$-0\cdot028_7$			$+0\cdot009_7$		
−1			$+0\cdot107_3$			$-0\cdot107_3$			$+0\cdot078_5$			$-0\cdot028_7$		
−1			$-0\cdot009_7$			$+0\cdot091_0$			$-0\cdot107_3$			$+0\cdot046_9$		
+1			$-0\cdot100_7$			$-0\cdot009_7$			$+0\cdot107_3$			$-0\cdot063_7$		
+1			$+0\cdot078_5$			$-0\cdot078_5$			$-0\cdot078_5$			$+0\cdot078_5$		
−1			$+0\cdot046_9$			$+0\cdot110_7$			$+0\cdot028_7$			$-0\cdot091_0$		
−1			$-0\cdot110_7$			$-0\cdot063_7$			$+0\cdot028_7$			$+0\cdot100_7$		
+1			$+0\cdot028_7$			$-0\cdot028_7$			$-0\cdot078_5$			$-0\cdot107_3$		
+1			$+0\cdot091_0$			$+0\cdot100_7$			$+0\cdot107_3$			$+0\cdot110_7$		
Sum of +terms			Sum of +terms			Sum of +terms			Sum of +terms			Sum of +terms		
Sum of −terms			Sum of −terms			Sum of −terms			Sum of −terms			Sum of −terms		
Sum total														
$0\cdot078_5+$ (Sum total) = $E_9 \cos a_9$			Sum total = $E_{11} \cos a_{11}$			Sum total = $E_{13} \cos a_{13}$			Sum total = $E_{15} \cos a_{15}$			Sum total = $E_{17} \cos a_{17}$		
$(E_9 \sin a_9)^2$			$(E_{11} \sin a_{11})^2$			$(E_{13} \sin a_{13})^2$			$(E_{15} \sin a_{15})^2$			$(E_{17} \sin a_{17})^2$		
$(E_9 \cos a_9)^2$			$(E_{11} \cos a_{11})^2$			$(E_{13} \cos a_{13})^2$			$(E_{15} \cos a_{15})^2$			$(E_{17} \cos a_{17})^2$		
E_9^2			E_{11}^2			E_{13}^2			E_{15}^2			E_{17}^2		
E_9			E_{11}			E_{13}			E_{15}			E_{17}		
$E_9 \sin a_9$			$E_{11} \sin a_{11}$			$E_{13} \sin a_{13}$			$E_{15} \sin a_{15}$			$E_{17} \sin a_{17}$		
$E_9 \cos a_9$			$E_{11} \cos a_{11}$			$E_{13} \cos a_{13}$			$E_{15} \cos a_{15}$			$E_{17} \cos a_{17}$		
a_9			a_{11}			a_{13}			a_{15}			a_{17}		

$+ \quad \sin(9\theta + \quad^\circ) + \quad \sin(11\theta + \quad^\circ) + \quad \sin(13\theta + \quad^\circ) + \quad \sin(15\theta + \quad^\circ) + \quad \sin(17\theta + \quad^\circ)$

TABLE 3.

			$E_1 \sin a_1$ terms			$E_3 \sin a_3$ terms			$E_5 \sin a_5$ terms		
	1	2	3 = 1 − 2 Difference	4 Constants	5 + or −	6 = 3 × 4	7 Constants	8 + or −	9 = 3 × 7	10 Constants	11 + or −	12 = 3 × 10
Differences	V_{75} =	V_{105} =		$+0{\cdot}086_3$			-1			$+0{\cdot}322_0$		
	V_{45} =	V_{135} =		$+0{\cdot}2357$			-1			$0{\cdot}2357$		
	V_{15} =	V_{165} =		$+0{\cdot}322_0$			$+1$			$+0{\cdot}086_3$		
				Sum of + terms			Sum of + terms			Sum of + terms		
				Sum of − terms			Sum of − terms			Sum of − terms		
							Sum total					
			A	Sum total $= E_1 \sin a_1$			$+0{\cdot}2357 \times$ (sum total) $= E_3 \sin a_3$			Sum total $= E_5 \sin a_5$		
			$E_1 \cos a_1$ terms				$E_3 \cos a_3$ terms			$E_5 \cos a_5$ terms		
	1	2	13 = 1 + 2 Sum	14 Constants	15 + or −	16 = 13 × 14	17 Constants	18 + or −	19 = 13 × 17	20 Constants	21 + or −	22 = 13 × 20
Sums	V_{75} =	V_{105} =		$+0{\cdot}322_0$			-1			$+0{\cdot}086_3$		
	V_{45} =	V_{135} =		$+0{\cdot}2357$			$+1$			$0{\cdot}2357$		
	V_{15} =	V_{165} =		$+0{\cdot}086_3$			$+1$			$+0{\cdot}322_0$		
				Sum of + terms			Sum of + terms			Sum of + terms		
				Sum of − terms			Sum of − terms			Sum of − terms		
							Sum total					
			B	Sum total $= E_1 \cos a_1$			$+0{\cdot}2357 \times$ (sum total) $= E_3 \cos a_3$			Sum total $= E_5 \cos a_5$		
			A^2	$(E_1 \sin a_1)^2$			$(E_3 \sin a_3)^2$			$(E_5 \sin a_5)^2$		
			B^2	$(E_1 \cos a_1)^2$			$(E_3 \cos a_3)^2$			$(E_5 \cos a_5)^2$		
			$A^2 + B^2$	E_1^2			E_3^2			E_5^2		
			$\sqrt{(A^2 + B^2)}$	E_1			E_3			E_5		
			A	$E_1 \sin a_1$			$E_3 \sin a_3$			$E_5 \sin a_5$		
			B	$E_1 \cos a_1$			$E_3 \cos a_3$			$E_5 \cos a_5$		
			$\tan^{-1}\left(\frac{A}{B}\right)$	a_1			a_3			a_5		

$V = \quad \sin(\theta + \quad^\circ) + \quad \sin(3\theta + \quad^\circ) + \quad \sin(5\theta + \quad^\circ)$

A modified set of constants, for use in connection with the approximate analysis of a wave up to the fifth harmonic, may be of value in some cases. For this purpose six ordinates are necessary, and they may be taken conveniently at 15°, 45°, 75°, 105°, 135° and 165° after the zero. Observing the same nomenclature as before, the equations shown in Table 4 are obtained.

It will be found convenient, for quickness in working, to arrange these approximate calculations also in the form of a schedule, an example of which is shown in Table 3.

If no harmonics higher than the fifth are present, the constants enumerated in Table 4 will give correct results, but, of course, the more pronounced the higher harmonics are, the larger the error will be in the determination of the equation to the wave by means of this second set of constants.

It will be observed that the corresponding coefficients in Tables 2 and 3 are not the same, since the two tables are evolved independently. The various coefficients follow definite formulæ, since they are obtained from different combinations of a number of known sines and cosines, but these formulæ have been omitted on account of their complexity.

Sometimes one or two harmonics stand out prominently on an experimental wave-form, and it is possible to determine their frequency by inspection. In a case like this it may be desirable to analyse the wave approximately into the fundamental and either one or two outstanding harmonics. Let the case be taken where a wave of this nature has two prominent harmonics of m and n times the frequency of the fundamental. The wave may therefore be represented by the expression :—

$$V = E_1 \sin(\theta + \alpha_1) + E_m \sin(m\theta + \alpha_m) + E_n \sin(n\theta + \alpha_n).$$

Taking six observations at $\theta = 15°, 45°, 75°, 105°, 135°$ and $165°$ as before, the following relations are obtained :—

$$V_{75} - V_{105} = 2E_1 \sin\alpha_1 \cos 75° + 2E_m \sin\alpha_m \cos 75m + 2E_n \sin\alpha_n \cos 75n$$
$$V_{75} + V_{105} = 2E_1 \cos\alpha_1 \sin 75° + 2E_m \cos\alpha_m \sin 75m + 2E_n \cos\alpha_n \sin 45n$$
$$V_{45} - V_{135} = 2E_1 \sin\alpha_1 \cos 45° + 2E_m \sin\alpha_m \cos 45m + 2E_n \sin\alpha_n \cos 45n$$
$$V_{45} + V_{135} = 2E_1 \cos\alpha_1 \sin 45° + 2E_m \cos\alpha_m \sin 45m + 2E_n \cos\alpha_n \sin 45n$$
$$V_{15} - V_{165} = 2E_1 \sin\alpha_1 \cos 15° + 2E_m \sin\alpha_m \cos 15m + 2E_n \sin\alpha_n \cos 15n$$
$$V_{15} + V_{165} = 2E_1 \cos\alpha_1 \sin 15° + 2E_m \cos\alpha_m \sin 15m + 2E_n \cos\alpha_n \sin 15n$$

Since the values of m and n are determined by inspection, it is an easy matter to separate out $E_1 \sin\alpha_1$, $E_1 \cos\alpha_1$, etc., and thus to evaluate the required amplitudes and phase angles.

This procedure is applicable to the case of the approximate determination of ripples, but the presence of any intermediate harmonics will, as before, affect the accuracy of these determinations.

TABLE 4.

$$E_1 \sin\alpha_1 = +0{\cdot}086_3(V_{75} - V_{105}) + 0{\cdot}235_7(V_{45} - V_{135}) + 0{\cdot}322_0(V_{15} - V_{165})$$
$$E_1 \cos\alpha_1 = +0{\cdot}322_0(V_{75} + V_{105}) + 0{\cdot}235_7(V_{45} + V_{135}) + 0{\cdot}086_3(V_{15} + V_{165})$$
$$E_3 \sin\alpha_3 = -0{\cdot}235_7(V_{75} - V_{105}) - 0{\cdot}235_7(V_{45} - V_{135}) + 0{\cdot}235_7(V_{15} - V_{165})$$
$$E_3 \cos\alpha_3 = -0{\cdot}235_7(V_{75} + V_{105}) + 0{\cdot}235_7(V_{45} + V_{135}) + 0{\cdot}235_7(V_{15} + V_{165})$$
$$E_5 \sin\alpha_5 = +0{\cdot}322_0(V_{75} - V_{105}) - 0{\cdot}235_7(V_{45} - V_{135}) + 0{\cdot}086_3(V_{15} - V_{165})$$
$$E_5 \cos\alpha_5 = +0{\cdot}086_3(V_{75} + V_{105}) - 0{\cdot}235_7(V_{45} + V_{135}) + 0{\cdot}322_0(V_{15} + V_{165})$$

NOTES ON THE ELECTRICAL CALCULATIONS OF LONG-DISTANCE HIGH-VOLTAGE TRANSMISSION LINES.*

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In studying the electrical characteristics of high-voltage long-distance transmission lines, the author has found that individual publications and papers on the matter deal so often with particular phases of the problem, or with particular cases, that it is difficult, without the perusal of a considerable amount of literature, to get a good grip of transmission-line problems. An attempt has therefore been made in compiling the following notes to get together the fundamental formulæ, particularly those embodying convergent series, and by way of illustration to show the application of the latter to the calculations of certain transmission lines referred to later.

In addition, the question of "constant-voltage transmission" is discussed, and proof given of the fundamental formulæ in connection with such transmission, and these formulæ are applied to the same transmission lines.

The methods of calculation indicated are those advocated by Mr. H. B. Dwight. Further, the theoretical matter in connection with constant-voltage transmission is elaborated considerably with a view to making the problem of constant-voltage transmission more easily understood than is the case from the bulk of the literature which the author has seen in connection with this subject.

The notes are divided into the following sections:—

Section 1.—Fundamental formulæ for transmission lines without branches.

Section 2.—The solution of a line 90 miles long delivering 25,000 kw. of three-phase 50-period energy at 100,000 volts, 80 per cent power factor, which solution includes a proof of the formulæ used for obtaining the various characteristics of the line.

Section 3.—Constant-voltage transmission with proof of the fundamental formula for the "circle diagram."

Section 4.—Calculation of the "circle diagram" for the line in Section 2.

Section 5.—Calculation of the capacity of synchronous condensers required for operating the line in Section 2 at constant voltage, together with the solution of the line characteristics when so operating.

Section 6.—The solution of a line 380 miles long delivering 18,000 kw. of three-phase 25-period energy at 130,000 volts.

Section 7.—Tables of line data, etc., necessary in making calculations.

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Section 1.

Fundamental Formulæ for Transmission Lines without Branches.

Let E be the voltage at the supply end,
I, „ current „ „ „
E „ voltage „ receiving end,
I „ current „ „ „
Y „ line admittance,
Z „ „ impedance,

then $$E_1 = E\cosh\sqrt{(YZ)} + \frac{1}{\sqrt{(YZ)}} I Z \sinh\sqrt{(YZ)} \qquad (1)$$

and $$I_1 = I\cosh\sqrt{(YZ)} + \frac{1}{\sqrt{(YZ)}} E Y \sinh\sqrt{(YZ)} \qquad (2)$$

(1) and (2) are the fundamental formulæ for transmission lines in terms of hyperbolic functions and, by their means, accurate solutions of transmission-line problems may be obtained.

The practical difficulty that arises in the use of these formulæ is that tables of values of $\cosh\sqrt{(YZ)}$ and $\sinh\sqrt{(YZ)}$ do not cover a close enough range of values, and it is therefore often necessary to interpolate values to correspond to a given problem. This introduces errors and, in many cases where interpolating has to be done, makes the solution only approximate.

The use of hyperbolic functions can be dispensed with by expanding $\cosh\sqrt{(YZ)}$ and $\sinh\sqrt{(YZ)}$ in ascending powers of $\sqrt{(YZ)}$. This gives *convergent series*, and has the advantage that no tables are required for line calculations other than those for the line characteristics such as resistance, reactance, capacity susceptance, etc.

These are as follows:—

$$E_1 = E\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2\cdot3\cdot4} \cdots\right) + IZ\left(1 + \frac{YZ}{2\cdot3} + \frac{Y^2Z^2}{2\cdot3\cdot4\cdot5} \cdots\right) \qquad (3)$$

$$\text{and } I_1 = I\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2\cdot3\cdot4} \cdots\right) + EY\left(1 + \frac{YZ}{2\cdot3} + \frac{Y^2Z^2}{2\cdot3\cdot4\cdot5} \cdots\right) \qquad (4)$$

Any degree of accuracy can be obtained by carrying the terms far enough, but in practice this is done only far enough for the values of the terms to become negligible in comparison with $\frac{1}{2}YZ$, and in most cases it will be found that there is no need to go beyond $\frac{Y^2Z^2}{2\cdot3\cdot4}$ and $\frac{Y^2Z^2}{2\cdot3\cdot4\cdot5}$.

Section 2.

Solution of 90-Mile 100,000-Volt Line, with Proof of Formulæ used in the Solution.

The conditions assumed are as follows :—

Power to be delivered	25,000 kw.
Phase and frequency	3 phase, 50 period
Voltage at receiver end of the line ...	100,000
Power factor at load	80 per cent
Size of each conductor	0000 B. & S.
Effective spacing of conductors ...	14 ft.
Reactance of transformers, coils, etc., at each end of the line	say, 6 per cent
Resistance of transformers, coils, etc., at each end of the line	say, 1 per cent
Length of line	90 miles

The methods of calculation deal with "total" current instead of current per line, and where the current per line is required it is necessary to divide the "total" current by $\sqrt{3}$.

$$\text{Total load current} = \frac{25{,}000 \times 1{,}000}{100{,}000 \times 0{\cdot}8} = 312{\cdot}5$$

$\therefore$ load current in phase with receiver voltage E

$$= 312{\cdot}5 \times 0{\cdot}8 = 250$$

and load current in quadrature with receiver voltage E

$$= 312{\cdot}5 \times 0{\cdot}6 = 187{\cdot}5$$

The resistance of the set of transformers, coils, etc., at the receiver end is specified as 1 per cent, i.e. 1 per cent of 100,000 volts is required to drive the "total" current through the resistance of the transformers, coils, etc.

$$\text{Therefore this resistance is} = \frac{1}{100} \times \frac{100{,}000}{312{\cdot}5} = 3{\cdot}2 \text{ ohms}$$

The resistance of the transformers at the generating end (i.e. the supply end) of the line is estimated to be the same, consequently the total resistance of the two sets of transformers and coils is $3{\cdot}2 \times 2 = 6{\cdot}4$ ohms.

The reactance of the set of the transformers, coils, etc., at the receiver end is estimated to be 6 per cent, and working this out in the same way as for the resistance we get

$$\text{reactance} = \frac{6}{100} \times \frac{100{,}000}{312{\cdot}5} = 19{\cdot}2 \text{ ohms}$$

With transformers of similar reactance at the generating end, the total reactance of the transformers at the two ends would be

$$19{\cdot}2 \times 2 = 38{\cdot}4 \text{ ohms}$$

This resistance and reactance will be added to those of the line to get the total resistance and reactance. The error introduced by doing this is negligible for practical engineering work.

It is also necessary to take account of the energy consumed by the transformers at no load, together with the magnetizing current. This is done by adding the watt component to the line leakage, and subtracting the magnetizing current from the line capacity current.

The watt component of the no-load current taken by each transformer is assumed to be 0·5 per cent of full-load current, or 0·5 per cent of 312·5 or

$$\frac{312{\cdot}5 \times 0{\cdot}5}{100} = 1{\cdot}562 \text{ amperes}$$

This is reduced to the value for insertion in the line admittance by dividing by the voltage at the receiver end, and is therefore

$$= \frac{1{\cdot}562}{100{,}000} = 0{\cdot}00001562$$

We may regard the transformers as reduced to an equivalent length of line and the above figure as the leakage due to that length of line. For the two transformers, one at each end of the line, the total leakage therefore will be

$$2 \times 0{\cdot}00001562 = 0{\cdot}00003124$$

The magnetizing current is taken as 5 per cent of full-load current, and will therefore be 10 times the value of the no-load energy figure.

Regarding the transformers as reduced to the equivalent length of line, we may regard the magnetizing current as added algebraically to the line admittance, and the figure filled in for the value of this for the two transformers will be 10 times that of the leakage or

$$10 \times 0{\cdot}00003124 = 0{\cdot}0003124$$

Line resistance.—A 0000 B. & S. stranded cable (7 wires) has a resistance, as got from the tables, of 0·2699 ohm per mile, at approximately 70° F.

$\therefore$ resistance of 90 miles $= 90 \times 0{\cdot}2699 = 24{\cdot}291$ ohms

Reactance.—The reactance per mile of a line with 14 ft. effective spacing is, from tables, $0{\cdot}343 \times 2$, and for 90 miles is

$$= 0{\cdot}343 \times 2 \times 90 = 61{\cdot}74 \text{ ohms}^*$$

Total resistance of one line including transformers, etc.

$$= 24{\cdot}291 + 6{\cdot}4 = 30{\cdot}691 \text{ ohms}$$

Total reactance of one line including transformers, etc.

$$= 61{\cdot}74 + 38{\cdot}4 = 100{\cdot}14 \text{ ohms}$$

Therefore *impedance of line* $Z = 30{\cdot}691 + i\,100{\cdot}14$.

We assume that the leakage due to the line proper is zero, because the line is being run below the corona limits of voltage, and the leakage from insulators, etc., is taken as zero, therefore the leakage due to the line proper = 0.

The capacity susceptance per mile of line from the tables

$$= 2{\cdot}17 \times 10^{-6} \times 2$$

and, therefore, for a 90-mile line is

$$= 2{\cdot}17 \times 10^{-6} \times 2 \times 90 = 0{\cdot}000389$$

Admittance due to the line proper is

$$0 + i\,0{\cdot}000389$$

Admittance due to transformers, etc., is

$$0{\cdot}00003124 - i\,0{\cdot}0003124$$

Therefore the *total admittance* Y

$$= 0{\cdot}00003124 + 0{\cdot}0000766$$

* The value 0·343 filled in is taken from the tables for 25 periods and is multiplied by 2 to give the value for 50 periods.

	A B	
From (3)	$E = 120{,}000 + i\,19{,}550$	see Appendix
Therefore	$E = 127{,}574$	
At no load	$I = 0$	

	A_0 B_0	
and again from (3)	$E = 90{,}064 + i\,273$	
Therefore	$E_0 = 90{,}065$	

	C D	
From (4)	$I = 252{\cdot}78 - i\,178{\cdot}53$	
Therefore	$I = 309{\cdot}47$	
At no load	$I = 0$	

	C_0 D_0	
and again from (4)	$I_0 = 37{\cdot}1135 + i\,7{\cdot}0543$	
Therefore	$I_0 = 8{\cdot}26$	

Certain numbers above have been designated with the letters A, B, C and D, A_0, B_0, C_0 and D_0. A and B are the portions of the voltage at the supply end of the line which are in phase and in quadrature respectively with E, the voltage at the receiver end. C and D are likewise portions of the current at the supply end which are in phase and in quadrature respectively with E.

In the same way A_0 and B_0 are the portions of the voltage at the supply end of the line at no load which are in phase and in quadrature with E. Similarly C_0 and D_0 are the portions of the current at the supply end of the line at no load which are in phase and in quadrature respectively with E.

It will therefore be evident that the voltage and current at the supply end at no load and full load will be the square root of the sum of the squares of the in-phase and quadrature portions.

Therefore
$$E = \sqrt{(A^2 + B^2)}$$
$$I = \sqrt{(C^2 + D^2)}$$
$$E_0 = \sqrt{(A_0^2 + B_0^2)}$$
$$I_0 = \sqrt{(C_0^2 + D_0^2)}$$

Various combinations of A, B, C, D, and A_0, B_0, C_0, D_0, give complete information regarding line regulation, efficiency, power factor at generating end, etc.

We will now prove the formulæ for the various characteristics of the line in terms of these symbols A, B, C, D, etc.

Full-load Conditions.

Voltage at receiver end = E.

Voltage at receiver end for constant supply volts.

At no load $I = 0$

Substituting this value in (3) we get

$$E_0 = E\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} + \ldots\right)$$

or
$$\frac{E_0}{E} = 1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} + \ldots$$

From this we see that the ratio of the voltages at the two ends of the line

$$= 1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} + \ldots \text{ at no load}$$

and is therefore constant, as the right-hand side of the equation is made up entirely of line constants. If, therefore, we want the voltage (say E) at no load at the receiver end of the line for constant supply voltage E_s, we also have

$$\frac{E}{E_0} = 1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} + \ldots \text{ and therefore } = \frac{E_s}{E}$$

$$\therefore E = E\frac{E}{E_0} \quad \text{or} \quad E_s = E \cdot \frac{\sqrt{(A^2 + B^2)}}{\sqrt{(A_0^2 + B_0^2)}}$$

The regulation at the receiver end from no load to full load for constant supply volts (i.e. change in voltage is $E_0 - E$ or

$$E \times \frac{\sqrt{(A^2 + B^2)}}{\sqrt{(A_0^2 + B_0^2)}} - E$$

or, expressed as a percentage of E,

the regulation at the receiver end for constant supply volts

$$= \frac{E \cdot \dfrac{\sqrt{(A^2 + B^2)}}{\sqrt{(A_0^2 + B_0^2)}} - E}{E} \quad 100\ \% \quad \ldots \quad (5)$$

The voltage at the supply end $= \sqrt{(A^2 + B^2)} \quad \ldots \quad (6)$

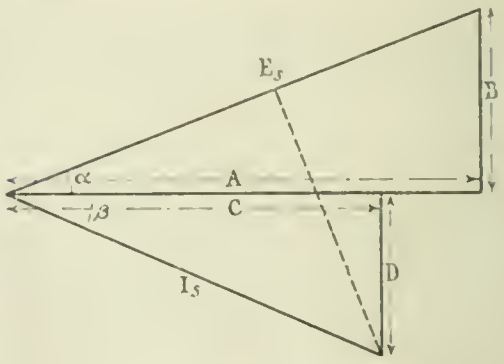

Fig. 1.

The regulation at the supply end for constant receiver volts

$$= \text{(voltage at full load)} - \text{(voltage at no load)}$$
$$= \sqrt{(A^2 + B^2)} - \sqrt{(A_0^2 + B_0^2)}$$

or, expressed as a percentage of full-load voltage,

the regulation at the supply end for constant receiver volts

$$= \frac{\sqrt{(A^2 + B^2)} - \sqrt{(A_0^2 + B_0^2)}}{\sqrt{(A^2 + B^2)}} \quad 100\ \% \quad \ldots \quad (7)$$

The current at the supply end at full load

$$= \sqrt{(C^2 + D^2)} \quad \ldots \quad (8)$$

The kilovolt-amperes at the supply end at full load

$$= \frac{1}{1{,}000}\sqrt{(A^2 + B^2)}\sqrt{(C^2 + D^2)} \quad \ldots \quad (9)$$

The kilowatts at the supply end are found by multiplying the current at that end which is in phase with the voltage

there, by the voltage, and dividing by 1,000. Fig. 1 shows that the current in phase with E_s

$$= I_s \cos(\alpha + \beta)$$

$$= I_s (\cos\alpha \,.\, \cos\beta - \sin\alpha \,.\, \sin\beta)$$

$$= I_s \left(\frac{A}{E_s} \cdot \frac{C}{I_s} + \frac{B}{E_s} \cdot \frac{D}{I_s}\right) \text{ since D is negative}$$

$$= \frac{A\,C + B\,D}{E_s}$$

Multiplying this by $\frac{E_s}{1{,}000}$ we get

$$\text{kilowatts at supply end} = \frac{1}{1{,}000}(A\,C + B\,D). \quad (10)$$

[NOTE.—Fig. 1 is drawn for a case where I_s is lagging behind E.

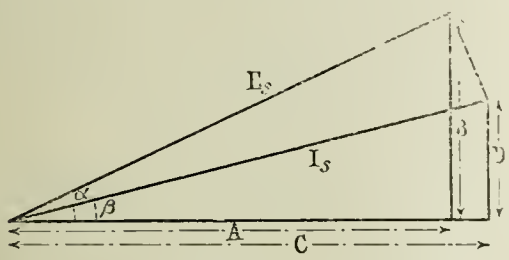

FIG. 2.

Fig. 2 shows a case where I_s leads E.

Here current in phase with $E = I_s \cos(\alpha - \beta)$

$$= I_s (\cos\alpha \,.\, \cos\beta + \sin\alpha \,.\, \sin\beta)$$

D is now positive, so that here again the value becomes $= \frac{A\,C + B\,D}{E_s}$, and therefore the expression for the kilowatts is, as before, $\frac{1}{1{,}000}(A\,C + B\,D)$.

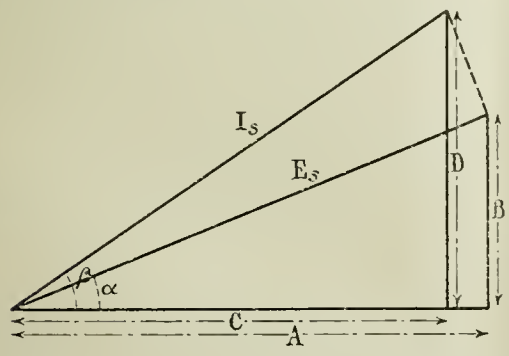

FIG. 3.

Fig. 3 shows a case where I_s leads E, and here again evidently kw. $= \frac{1}{1{,}000}(A\,C + B\,D)$.

Hence $\frac{1}{1{,}000}(A\,C + B\,D)$ is the general expression for the kilowatts at the supply end.]

The power factor at the supply end $= \frac{\text{kw.}}{\text{k.v.a.}} \times 100\ \%$

$$= \frac{A\,C + B\,D}{\sqrt{(A^2 + B^2)}\,\sqrt{(C^2 + D^2)}} \times 100\ \% \quad . \quad . \quad . \quad (11)$$

The in-phase current at supply end in total amperes

$$= \frac{\text{kw.} \times 1{,}000}{\text{volts}} = \frac{A\,C + B\,D}{\sqrt{(A^2 + B^2)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The reactive k.v.a. at the supply end

$$= \frac{(\text{current in quadrature}) \times \text{voltage}}{1{,}000}$$

$$= I_s \,.\, \sin(\alpha + \beta) \,.\, E_s \div 1{,}000$$

$$= \frac{I_s E_s}{1{,}000} \,.\, (\sin\alpha\cos\beta + \cos\alpha\sin\beta)$$

$$= \frac{I_s E_s}{1{,}000}\left(\frac{B\,C}{E_s I_s} - \frac{A\,D}{E_s I_s}\right) \text{ since D is negative}$$

$$= \frac{B\,C - A\,D}{1{,}000} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

It is necessary to know whether this reactive k.v.a. is leading or lagging, in order to determine whether the power factor at the supply end is leading or lagging.

If the expression (B C − A D) is positive, the current at the supply end, and also the reactive kilovolt-amperes, are lagging.

If the expression (B C − A D) is negative, then the current at the supply end, and also the reactive kilovolt-amperes, are leading.

The reactive current at the supply end in total amperes

$$= \frac{\text{reactive k.v.a.} \times 1{,}000}{\text{volts}}$$

Therefore reactive current at the supply end in total amperes

$$= \frac{B\,C - A\,D}{\sqrt{(A^2 + B^2)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The kw. loss in line

= (kw. input into line) − (kw. output taken from line)

The kw. input as proved above $= \frac{1}{1{,}000}(A\,C + B\,D)$.

The output from the line

$$= \frac{E \times (\text{total amps. of load in phase with E})}{1{,}000}$$

If we designate the load amperes in phase with E as P, then the output $= \frac{E\,P}{1{,}000}$

Therefore kw. loss in line

$$= \frac{1}{1{,}000}(A\,C + B\,D - E\,P) \quad . \quad . \quad . \quad (15)$$

The percentage efficiency of the line $= \frac{\text{kw. output}}{\text{kw. input}}\ 100\ \%$

Therefore percentage efficiency of line

$$= \frac{E\,P}{A\,C + B\,D}\ 100\ \% \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

NO-LOAD CONDITIONS.

The proof of the following formulæ for the various characteristics of the line at no load are exactly similar to those given above for the full-load condition.

The voltage at the receiver end for constant voltage at supply end is, as shown above

$$= \frac{\sqrt{(A^2 + B^2)}}{\sqrt{(A^2 + B^2)}} \times E \quad . \quad . \quad . \quad . \quad . \quad (17)$$

The voltage at the supply end for constant receiver voltage is as shown above

$$= \sqrt{(A^2 + B^2)} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

Current at supply end $= \sqrt{(C^2 + D^2)}$ . . . . . (19)

Kilovolt-amperes at supply end

$$= \frac{1}{1,000} \sqrt{(A^2 + B^2)} \sqrt{(C^2 + D^2)} \quad . \quad (20)$$

Kilowatts at supply end $= \frac{1}{1,000} (A C + B D)$ . . (21)

Power factor at supply end in percentage

$$= \frac{A C + B D}{\sqrt{(A^2 + B^2)} \sqrt{(C^2 + D^2)}} 100 \% \quad . \quad . \quad (22)$$

In-phase current in total amperes $= \frac{A C + B D}{\sqrt{(A^2 + B^2)}}$. (23)

Reactive current in total amperes $= \frac{B C - A D}{\sqrt{(A^2 + B^2)}}$. (24)

(If *positive*, current is lagging. If *negative*, current is leading.)

Kilowatt loss in line

$$= \frac{1}{1,000} (A_1 C + B_1 D_1) \text{ as there is no load} \quad . \quad (25)$$

Application of these Formulæ to above Line.

Full-Load Conditions.

$$E_0 = E \frac{\sqrt{(A^2 + B^2)}}{\sqrt{(A^2 + B^2)}} = 100 (0 + i) \times \frac{127{\cdot}574}{99{\cdot}665} = 128{\cdot}03$$

where will be the voltage at no load at the receiver end for constant voltage at the supply end.

The regulation at the receiver end for constant supply voltage will therefore be

$$\frac{128{\cdot}03 - 100{\cdot}000}{100{\cdot}000} \times 100 = 28{\cdot}0 \%$$

The voltage at the supply end at full load for 100·000 volts at receiver end

$$= \sqrt{(A^2 + B^2)} = 127{\cdot}574$$

The regulation at the supply end for constant receiver volts

$$\sqrt{(A^2 + B^2)} - \sqrt{(A_1^2 + B_1^2)} = 127{\cdot}574 - 99{\cdot}665 = 27{\cdot}909$$

or as a percentage $\frac{27{\cdot}909}{127{\cdot}574} \times 100 = 21{\cdot}88 \%$

The current at the supply end in total amperes at full load

$$= \sqrt{(C^2 + D^2)} = 8{\cdot}26 \text{ (amperes per wire} = 4{\cdot}13)$$

Kilovolt-amperes at the supply end at full load

$$= \frac{1}{1,000} \sqrt{(A^2 + B^2)} \sqrt{(C^2 + D^2)}$$

$$= \frac{1}{1,000} \times 127{\cdot}574 \times 300{\cdot}47 = 30{\cdot}480$$

Kilowatts at the supply end at full load $= \frac{1}{1,000} (A C + B D)$

$$= \frac{1}{1,000} \left[120,000 \times 252{\cdot}78 + 10{\cdot}556 \times (-178{\cdot}53) \right]$$

$$= \frac{1}{1,000} (31,807,000 - 3,491,400)$$

$$= 28{\cdot}375 \text{ kw.}$$

The power factor at the supply end at full load

$$= \frac{\text{kw.}}{\text{k.v.a.}} 100 \% = \frac{28{\cdot}375}{30{\cdot}480} \times 100 \% = 71{\cdot}87 \%$$

(lagging, see below)

The in-phase current at supply end in total amperes :

$$\frac{A C + B D}{\sqrt{(A^2 + B^2)}} = \frac{\text{kw.} \times 1,000}{\text{volts}} = \frac{28,375,000}{127{\cdot}574} = 222{\cdot}4$$

therefore the in-phase amperes will be 128·4 per wire.

The reactive k.v.a. at supply end in total amperes

$$\frac{B C - A D}{1,000} = \frac{10{\cdot}556 \times 252{\cdot}78 - 120,000 \times (-178{\cdot}53)}{1,000}$$

$$= \frac{4,043,500 + 22,500,000}{1,000}$$

$$= 27{\cdot}450.$$

The reactive current at supply end in total amperes :

$$\frac{B C - A D}{\sqrt{(A^2 + B^2)}} = \frac{\text{reactive k.v.a.} \times 1,000}{\text{volts}}$$

$$= \frac{27{\cdot}450 \times 1,000}{127{\cdot}574} = 215{\cdot}2$$

Therefore reactive current per wire = 124·25, and as the sign is positive, it is lagging.

The kw. loss in line, etc. = (kw. line input) − (kw. line output)

$$\frac{1}{1,000} (A C + B D - E I) = 28{\cdot}375 - 25{\cdot}000 = 3{\cdot}375 \text{ kw.}$$

The per cent efficiency of line, including transformers, etc.

$$\frac{E I}{A C + B D} \times 100 = \frac{\text{kw. output}}{\text{kw. input}} = \frac{25{\cdot}000}{28{\cdot}375} = 88{\cdot}1 \%$$

No-load Conditions.

The voltage at the receiver end for constant voltage at the supply end is shown above to be 128·03.

The voltage at the supply end for constant receiver volts is

$$= \sqrt{(A_1^2 + B_1^2)} = 99{\cdot}665$$

Current at the supply end $= \sqrt{(C_1^2 + D_1^2)} = 8{\cdot}26$

The kilovolt-amperes at the supply end

$$= \frac{1}{1,000} (\text{amps.}) (\text{volts}) = \frac{1}{1,000} 8{\cdot}26 \times 99{\cdot}665 = 823$$

As this is a positive quantity, this gives a lagging k.v.a. and therefore the power factor found above is lagging.

The kilowatts at the supply end

$$= \frac{1}{1,000}(A_o C_o + B_o D_o)$$
$$= \frac{1}{1,000}(99,664 \times 3{\cdot}11 + 273{\cdot}6 \times 7{\cdot}65)$$
$$= (309{\cdot}95 + 2{\cdot}09)$$
$$= 312$$

Power factor at the supply end in percentage

$$\frac{\text{kw.}}{\text{k.v.a.}} = \frac{312}{823} \times 100\ \% = 37{\cdot}9\ \%.$$

(leading, see below)

The in-phase current in total amperes

$$= \frac{\text{kw.} \times 1,000}{\text{volts}} = \frac{312,000}{99,665} = 3{\cdot}13$$

in total amperes or in-phase amperes per wire $= 1{\cdot}87$.

Reactive current in total amperes $= \dfrac{B_o C_o - A_o D_o}{\sqrt{(A_o^2 + B_o)}}$

$$= \frac{273{\cdot}6 \times 3{\cdot}11 - 99,664 \times 7{\cdot}65}{99,665}$$

$$= \frac{-761,580}{99,665} = -7{\cdot}65$$

or reactive amperes per wire $= -4{\cdot}41$ (as this is negative the power factor is leading).

Kilowatt loss in line, etc.,

$$\frac{1}{1,000}(A_o C_o + B_o D_o) = 312 \text{ (as there is no load)}$$

Conditions Specified at Supply End of Line.

The whole of the foregoing refers to a case where the conditions are specified at the receiver end of the line.

Where the conditions are given at the supply end and it is desired to find those at the receiver end, then fundamental formulæ (3) and (4) become

$$E = E_s\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right) - I_s Z\left(1 + \frac{YZ}{2 \cdot 3} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4 \cdot 5} \cdots\right) \quad (26)$$

$$\text{and } I = I_s\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right) - E_s Y\left(1 + \frac{YZ}{2 \cdot 3} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4 \cdot 5} \cdots\right) \quad (27)$$

since power is now flowing away from the point where the conditions are known, namely the supply end.

The same procedure as before is followed to obtain the quantities for voltage and current at the receiver end. Call the in-phase and quadrature portions of the voltage at the receiver end F and G respectively, and the in-phase and quadrature portions of the current at the receiver end H and K respectively. Combinations of F, G, H and K give us information required regarding the conditions that will obtain at the receiver end when the line is loaded.

At no load, however, the conditions are not all specified at the supply end. For example, we do not know the kilovolt-amperes at the supply end or the current. We only know that the load is zero at the receiver end.

We have previously seen that the ratio of the voltages at the two ends of the line at no-load is equal to

$$\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right)$$

therefore $E_o = E_s \div \left(1 + \dfrac{YZ}{2} + \dfrac{Y^2Z^2}{2 \cdot 3 \cdot 4} + \cdots\right)$

expanding this we get

$$E_o = E_s\left(1 - \frac{YZ}{2} + \frac{5}{24}Y^2Z^2 - \frac{61}{720}(Y^3Z^3) + \frac{277}{8,064}Y^4Z^4 \cdots\right) \quad (28)$$

This gives us vector quantities for E_o. Call them F_o and G_o. With the load as zero we get from (4)

$$I_{so} = E_o Y\left(1 + \frac{YZ}{2 \cdot 3} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4 \cdot 5} + \cdots\right)$$

substituting the value for E_o from (28) we get

$$I_{so} = E_s Y\left(1 - \frac{YZ}{2} + \frac{5}{24} \times Y^2Z^2 \cdots\right)\left(1 + \frac{YZ}{2 \cdot 3} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4 \cdot 5} \cdots\right)$$

The above series are now multiplied together by ordinary algebraic methods and we get

$$I_{so} = E_s Y\left(1 - \frac{1}{3}YZ + \frac{2}{15}Y^2Z^2 - \frac{17}{315}Y^3Z^3 + \frac{62}{2,835}Y^4Z^4 \cdots\right) \quad (29)$$

This gives us two vector quantities for the current at the supply end when no load is taken from the receiver end. Call these quantities H_o and K_o.

We will now show that various combinations of F, G, H, K, and F_o, G_o, H_o, K_o, give us the conditions obtaining in the line at full load and no load.

The voltage E at the receiver end

$$= \sqrt{(F^2 + G^2)} \text{ at full load} \quad (30)$$

The voltage E_o at the receiver end

$$= \sqrt{(F_o^2 + G_o^2)} \text{ at no load} \quad (31)$$

The regulation at the receiver end for constant voltage E at the supply end is the rise in voltage between no load and full load and is therefore

$$= \sqrt{(F_o^2 + G_o)} - \sqrt{(F^2 + G^2)}$$

or as a percentage of full-load voltage E, at the receiver end

$$\text{Regulation} = \frac{\sqrt{(F_o^2 + G_o^2)} - \sqrt{(F^2 + G^2)}}{\sqrt{(F^2 + G^2)}} \times 100\ \% \quad (32)$$

If we require constant voltage E at the receiver end, we would get a voltage (call it E_{so}) at the supply end where

$$\frac{E_{so}}{E} = \left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right) = \frac{E_s}{E_o}$$

Therefore

$$E_{so} = \frac{E_s}{E_o} E$$
$$= E \frac{\sqrt{(F^2 + G^2)}}{\sqrt{(F^2 + G_o)}}$$

Therefore for constant voltage E at the receiver end, the voltage at the supply end would change from E at full load to

$$E_0 \text{ or } \frac{\sqrt{(F^2+G^2)}}{\sqrt{(F_0^2+G_0^2)}} E \text{ at no load}$$

Therefore the regulation at the supply end for constant voltage E at the receiver end would be

$$E_0 - \frac{\sqrt{(F^2+G^2)}}{\sqrt{(F_0^2+G_0^2)}} E$$

or as a percentage of E_0 the regulation at the supply end for constant voltage E at the receiver end

$$= \frac{E_0 - \frac{\sqrt{(F^2+G^2)}}{\sqrt{(F_0^2+G_0^2)}} E}{E_0} 100\ \% \quad . \quad . \quad . \quad . \quad (33)$$

The current in total amperes at the receiver end at full load would be

$$= \sqrt{(H^2+K^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

The current at the supply end for no load would similarly be

$$= \sqrt{(H_0^2+K_0^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

The kilovolt-amperes at the receiver end at full load

$$= \frac{\sqrt{(F^2+G^2)}\sqrt{(H^2+K^2)}}{1{,}000} \quad . \quad . \quad . \quad . \quad (36)$$

The kilovolt-amperes at the supply end at no load would be

$$= \frac{1}{1{,}000} F \sqrt{(H_0^2+K_0^2)} \quad . \quad . \quad . \quad . \quad (37)$$

The kilowatts at the receiver end at full load would be

$$= \frac{1}{1{,}000} (F H + G K) \quad . \quad . \quad . \quad . \quad . \quad (38)$$

The proof of this is similar to that in the case of conditions given at the receiver end, which is covered in the earlier part of this paper.

Kilowatts at the supply end at no load would be

$$\frac{1}{1{,}000} E \times H_0 \quad . \quad . \quad . \quad . \quad . \quad (39)$$

The power factor in per cent at receiver end at full load

$$= \frac{(F H + G K)}{\sqrt{F^2+G^2}\sqrt{H^2+K^2}} 100\ \% \quad . \quad . \quad . \quad (40)$$

The power factor in per cent at the supply end at no load

$$= \frac{H}{\sqrt{(H^2+K^2)}} 100\ \% \quad . \quad . \quad . \quad . \quad . \quad (41)$$

The in-phase current in total amperes at the receiver end at full load

$$= \frac{(F H + G K)}{\sqrt{(F^2+G^2)}} \quad . \quad . \quad . \quad . \quad . \quad (42)$$

The in-phase current in total amperes at the supply end at no load

$$= H_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

The reactive current in total amperes at the receiver end at full load

$$= \frac{G H - F K}{\sqrt{(F^2+G^2)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

[NOTE.—This can be proved, as near the beginning of this paper, for a case where the conditions are given at the receiver end.]

If positive, the current is lagging. If negative, the current is leading.

The reactive current in total amperes at the supply end at no load

$$= K \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

The kilowatt loss in line at full load

$$= \frac{1}{1{,}000} [E\ P - (F H + G K)] \quad . \quad . \quad . \quad (46)$$

where P is the current in phase with E.

The kilowatt loss in line at no load

$$= \frac{1}{1{,}000} E H_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

The percentage efficiency of the line at full load

$$= \frac{F H + G K}{E P} \times 100\ \% \quad . \quad . \quad . \quad . \quad (48)$$

SECTION 3.

CONSTANT VOLTAGE TRANSMISSION.

The foregoing portion has dealt with varying voltage lines, i.e. with lines where with constant supply voltage the voltage at the receiver end will vary with the load, or with lines where, in order to maintain constant voltage at the receiver end, the voltage has to be varied at the supply end with varying load.

On such lines the limiting factor, as regards the load which they can carry, is the regulation, and in actual practice the load which it is possible to carry over such lines is far below the current-carrying capacity of the conductors.

If, however, a sufficient capacity of synchronous condensers (or as they are often called "phase modifiers") is connected to the line, not only can the voltage at both ends of the line be maintained constant over the whole range of load, but the loading of the line can be very materially increased for a given voltage difference between the ends of the line.

We will now show why this is so and prove the fundamental formulæ, from which what is known as the "circle diagram" is obtained.

If the load is zero then I = 0. From (3) we get

$$E_0 = E \left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right)$$

The right-hand side of this last equation gives vector quantities (call them F_1 and E_2), so that the equation may be written

$$E_0 = E_1 + i E_2$$

* These quantities E_1 and E_2 are actually the same as A and B in Section 2, but we have designated them by different letters here to distinguish them in this portion, which deals with constant voltage.

An examination of the expression

$$E\left(1+\frac{YZ}{2}+\frac{Y^2Z^2}{2\cdot3\cdot4}\cdots\right)$$

will show that if E is kept constant, the expression is a constant because Y and Z are line characteristics and are therefore constant for a given line. Consequently E_1 and E_2 are constant if E is constant.

Referring to the second portion of the right-hand side of equation (3), namely

$$IZ\left(1+\frac{YZ}{2\cdot3}+\frac{Y^2Z^2}{2\cdot3\cdot4\cdot5}\cdots\right)$$

we see that the portion multiplied on I, namely

$$Z\left(1+\frac{YZ}{2\cdot3}+\frac{Y^2Z^2}{2\cdot3\cdot4\cdot5}\cdots\right)$$

is constant and gives us two vector quantities (call them R and X_1) so that

$$Z\left(1+\frac{YZ}{2\cdot3}+\frac{Y^2Z^2}{2\cdot3\cdot4\cdot5}+\cdots\right)=R_1+iX_1$$

Equation (3) may therefore be written as follows

$$E_s=E_1+iE_2+I(R_1+iX_1)$$

An examination of this equation shows that E_s, the voltage at full load, may be regarded as made up of the voltage required at no load plus the voltage required to drive the current I through the impedance (R_1+iX_1).

As I itself is made up of two vector quantities (call them P in phase, and Q in quadrature) I may be written in the form $P+iQ$. Therefore the above equation can be written

$$E_s=E_1+iE_2+(P+iQ)(R_1+iX_1)$$

or multiplying out we get

$$E_s=(E_1+PR_1-QX_1)+i(E_2+PX_1+QR_1)$$

E_s may therefore be regarded as made up of one quantity $(E_1+PR_1-QX_1)$ in phase, and another quantity $(E_2+PX_1+QR_1)$ in quadrature, which is only another way of saying that

$$E_s^2=(E_1+PR_1-QX_1)^2+(E_2+PX_1+QR_1)^2 \quad . \quad (49)$$

If constant voltage is to be maintained at the receiver end, we may regard E_s, E_1, R_1, X_1, E_2 as constants. Therefore the only variables in this equation are P (the in-phase portion of the current at the receiver end of the line) and Q (the quadrature portion of the current at the receiver end of the line).

Multiplying out equation (49) we get

$$P^2(R_1^2+X_1^2)+Q^2(R_1^2+X_1^2)+2P(E_1R_1+E_2X_1)-2Q(E_1X_1-E_2R_1)+E_1^2+E_2^2-E_s^2=0$$

or dividing across by $R_1^2+X_1^2$ we get

$$P^2+Q^2+2P\frac{E_1R_1+E_2X_1}{R_1^2+X_1^2}-2Q\frac{E_1X_1-E_2R_1}{R_1^2+X_1^2}+\frac{E_1^2+E_2^2-E_s^2}{R_1^2+X_1^2}=0 \quad . \quad (50)$$

which is the standard form for the equation of a circle.

The equation of the circle shown in Fig. 4 is obviously

$$(x-a)^2+(y-b)^2=c^2$$

where (a, b) is the centre and (c) the radius. Multiplying these out and arranging them in descending powers of x and y we get

$$x^2+y^2-2ax-2by+a^2+b^2-c^2=0 \quad . \quad (51)$$

Referring to the circle represented by equation (50), let us call its centre (a_1, b_1) and its radius (c_1). It will be seen by comparing equations (50) and (51) that

$$a_1=-\frac{E_1R_1+E_2X_1}{R_1^2+X_1^2}$$

$$b_1=+\frac{E_1X_1-E_2R_1}{R_1^2+X_1^2}$$

and

$$a_1^2+b_1^2-c_1^2=+\frac{E_1^2+E_2^2-E_s^2}{R_1^2+X_1^2}$$

substituting in this last the above values for a_1 and b_1 we get

$$c_1=\frac{E_s}{\sqrt{(R_1^2+X_1^2)}}$$

The values given above for a_1, b_1, and c_1 are evidently in terms of current. As will be seen later from consideration

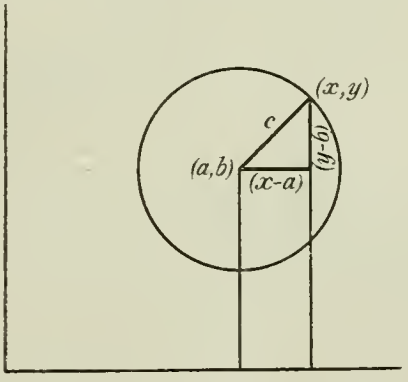

FIG. 4.

of the circle diagram, it is more convenient that this diagram should be drawn in terms of kilowatts and kilovolt-amperes. If, therefore, we multiply the above values of a_1, b_1, and c_1 by the voltage at the receiver end, namely E, and divide by 1,000, we get values for the centre and radius of the circle which will be in terms of kw. and k.v.a. Call the centre of this circle (a_2, b_2) and the radius (c_2). It will now be evident that the values of a_2, b_2, and c_2 are as follows

$$a_2=-\frac{E}{1{,}000}\times\frac{E_1R_1+E_2X_1}{R_1^2+X_1^2} \quad . \quad . \quad . \quad (52)$$

$$b_2=+\frac{E}{1{,}000}\times\frac{E_1X_1-E_2R_1}{R_1^2+X_1^2} \quad . \quad . \quad . \quad (53)$$

and

$$c_2=\frac{E}{1{,}000}\times\frac{E_s}{\sqrt{(R_1^2+X_1^2)}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

Section 4.

Calculations for Circle Diagram for Line in Section 2.

We can now calculate the actual values of a_2, b_2, and c_2 by finding the values of E_1, E_2, and R_1, X_1. E_1 and E_2, from the manner of their derivation, are evidently the portions of the supply voltage at no load which are in phase and in quadrature respectively with E the receiver

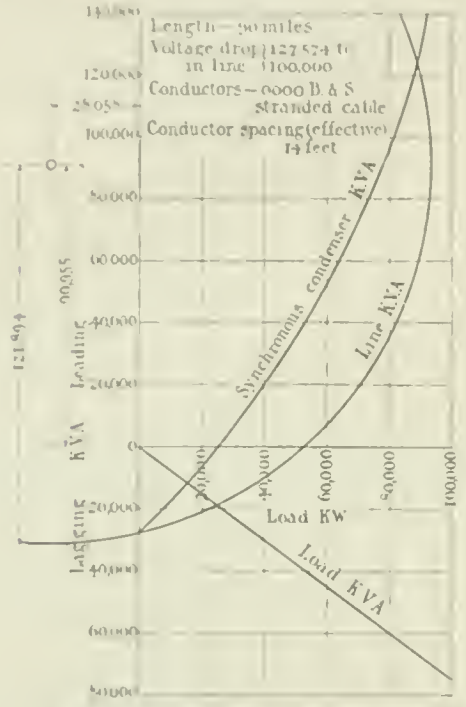

Fig. 5.—Circle diagram for high-tension, constant-voltage, three-phase, 50 period transmission line.

voltage. These have been previously calculated in Section 2, where they are designated as A and B.

Therefore $E_1 = 99{,}604$

and $E_2 = 273{\cdot}0$

R_1 and X_1 from the manner of their derivation are the two vector portions which make up the expression

$$Z\left(1 + \frac{YZ}{2\cdot3} + \frac{Y^2Z^2}{2\cdot3\cdot4\cdot5} \cdots\right)$$

Therefore $R_1 = 30{\cdot}505$

$X_1 = 100{\cdot}05$

But $$a_2 = -\frac{E_1}{1{,}000} \times \frac{E_1 R_1 + E_2 X_1}{R_1^2 + X_1^2}$$

From which we get $a_2 = -28{,}058$ kw. . . . . (55)

$$b_2 = \frac{E_1}{1{,}000} \times \frac{E_1 X_1 - E_2 R_1}{R_1^2 + X_1^2}$$

from which we get $b_2 = +99{,}955$ k.v.a. . . . . (56)

Again $$c_1 = \frac{E_1}{1{,}000} \times \frac{E_1}{\sqrt{R_1^2 + X_1^2}}$$

or $c_1 = 121{,}894$ . . . . . (57)

The circle diagram constructed from the above data is shown in Fig. 5. After drawing the circle from the values of a_2, b_2 and c_2 a line is drawn in at the correct angle (in this case cos $^{-1}0{\cdot}8$) to represent the load. The ordinates of this circle and line are added and the resulting ellipse drawn in. For a given kw. load the ordinate of the ellipse corresponding to that load will give the k.v.a. required from the synchronous plant to maintain the voltage at that load.

This circle diagram, carefully drawn, will give very accurate information with regard to the capacity of synchronous plant required, but this can be calculated for no load or for any load as set out below.

Section 5.

Calculation of Capacity of "Synchronous Condensers" required for Operating the Line in Section 2 at Constant Voltage, together with the Solution of the Line Characteristics when so Operating.

The fundamental equation for the circle as given in (50) is

$$P^2 + Q^2 + 2P\frac{E_1 R_1 + E_2 X_1}{R_1^2 + X_1^2} - 2Q\frac{E_1 X_1 - E_2 R_1}{R_1^2 + X_1^2} + \frac{E_1^2 + E_2^2 - E^2}{R_1^2 \times X_1^2} = 0$$

If we desire to ascertain the amount of synchronous plant to hold the voltage down to E (i.e. 100,000) at no load, we would evidently get it by making $P = 0$ in the above equation and solving for Q.

Making $P = 0$ we get

$$Q^2 - Q \times 2\frac{(E_1 X_1 - E_2 R_1)}{R_1^2 + X_1^2} + \frac{E_1^2 + E_2^2 - E^2}{R_1^2 + X_1^2} = 0$$

or $$Q^2 - Q \times 1{,}819{\cdot}10 - 578{,}050 = 0$$

or $$Q = \frac{1{,}819{\cdot}10 \pm \sqrt{[(1{,}819{\cdot}10^2 + 4(578{,}050)]}}{2}$$

This gives two values of Q corresponding to the plus and minus signs of the radical. The two values are evidently the points at which the ordinate through the origin cuts the circle. It will be evident from an inspection of the circle diagram that we require the value of Q corresponding to the minus sign of the radical which gives us

$$Q = -276{\cdot}29$$

This is the quadrature current required from the synchronous plant at no load, and is lagging. The kilovolt-amperes will therefore be

$$-276{\cdot}29 \times \frac{100{,}000}{1{,}000} = -27{,}629 \text{ k.v.a.}$$

We therefore find that, in order to hold the voltage down to 100,000 at the receiver end at no load, the synchronous plant must be capable of giving 27,629 k.v.a. of lagging quadrature current.

Synchronous plant of this capacity can, with modification of the field excitation, be made to give a similar capacity of leading quadrature current. We shall therefore now inquire what load can be carried on the line if 276·29 amperes of leading quadrature current are supplied to the line from the synchronous plant.

By an inspection of the circle diagram, it will be evident that for a given load P (in amperes) we shall have to supply such an amount of quadrature current to the line as will bring the point corresponding to P on the load line on to the circle, because we shall then get the point (P, Q) on the circle.

For any load P the load reactive current will be P tan θ, where θ is the angle of lag of the load.

For a given load P it will be evident from an inspection of the circle diagram that, in order to get from the load line to the circle, we shall have to add to the load reactive current (with due regard to sign) an amount of reactive current $=$ (P tan θ + Q), or in other words :

For any load P the amount of reactive current required from the synchronous plant is

$$= P \tan \theta + Q \quad . \quad . \quad . \quad . \quad . \quad . \quad (58)$$

or in k.v.a. is

$$= \frac{E}{1{,}000} (P \tan \theta + Q) \quad . \quad . \quad . \quad . \quad (59)$$

If in equation (50) we substitute the value P for any load and solve for Q, we shall get the corresponding value for Q required in equation (58), and inserting the value Q so obtained in (59) we shall get the amount of reactive k.v.a. required from the synchronous plant at any load P.

We now return to the solution of what load 276·29 reactive amperes supplied leading from the synchronous plant will enable us to carry if added to the line. From equation (58) we get

$$276{\cdot}29 = P \tan \theta + Q$$

Tan θ in this case $= 0{\cdot}75$.

Therefore

$$Q = 276{\cdot}29 - P \times 0{\cdot}75 \quad . \quad . \quad . \quad . \quad (60)$$

Substituting this value in equation (50) and solving for P we shall get the load which the addition of 276·29 leading reactive amperes from the synchronous plant will enable us to carry on the line and maintain constant voltage.

Substituting in (50) the above value for Q we get

$$P^2 + (276{\cdot}29)^2 - 2 \times 0{\cdot}75 \times 276{\cdot}29\, P + (0{\cdot}75)^2 P^2 + 2 P \times 280{\cdot}58 - 2(276{\cdot}29 - 0{\cdot}75\, P) \times 909{\cdot}55 - 578{,}950 = 0$$

or

$$1{\cdot}5625\, P^2 + 1{,}511{\cdot}05\, P - 1{,}005{,}210 = 0$$

Therefore

$$P = \frac{-1{,}511{\cdot}05 \pm \sqrt{[(1{,}511{\cdot}05)^2 - 4 \times 1{\cdot}5625 \times (-1{,}005{,}210)]}}{2 \times 1{\cdot}5625}$$

Take + sign evidently.

Therefore

$$P = 453{\cdot}02$$

Multiplying this by $\frac{E}{1{,}000}$, i.e. $\frac{100{,}000}{1{,}000}$, we get 45,302 kw.

We therefore arrive at the conclusion that the use of 27,629 k.v.a. of synchronous plant required to hold the voltage down to 100,000 at no load will enable us to maintain the voltage constant up to a load of 45,302 kw.

In other words, the addition of this amount of synchronous plant has enabled us to increase the loading of the line by 81·21 per cent with the same drop in voltage between the ends of the line that enabled us to carry 25,000 kw. when the line was operated as a varying voltage line. Not only has the load which the line can carry with this drop been increased to the extent indicated, but regulation troubles have been eliminated, as the line is operated with constant voltage at both ends over the whole range of load from zero to 45,302 kw.*

In order to get complete information regarding the line when carrying this greatly increased load of 45,302 kw., it is necessary to complete the solution of the line and ascertain its efficiency, power factor at the generators, etc. In order to get this information we require to calculate the quantities corresponding to A, B, C, and D in Section 2, where we were calculating similar characteristics for the line operating without synchronous condensers and loaded to 25,000 kw. Call the corresponding quantities A_c, B_c, C_c, and D_c. A_c will be the voltage at the supply end which is in phase with E ; B_c will be the voltage at the supply end in quadrature with E ; C_c will be the current in the line at the supply end in phase with E ; and D_c will be the current in the line at the supply end in quadrature with E.

An examination of equation (49) will show that

$$A_c = E_1 + P R_1 - Q X_1$$

and

$$B_c = E_2 + P X_1 + Q R_1$$

In these equations we know the values of E_1, E_2, R_1, X_1, and P, but we have to calculate the value of Q corresponding to $P = 453{\cdot}02$.

We know from equation (60) that $Q = 276{\cdot}29 - 0{\cdot}75\, P$ when the load $= 45{,}302$ kw., i.e. when $P = 453{\cdot}02$.

Therefore

$$Q = 276{\cdot}29 - 0{\cdot}75 \times 453{\cdot}02 = -63{\cdot}475$$

Therefore

$$A_c = 99{,}664 + 453{\cdot}02 \times 30{\cdot}565 + 63{\cdot}475 \times 100{\cdot}056$$

Therefore

$$A_c = 119{,}862$$

$$B_c = 273{\cdot}60 + 453{\cdot}02 \times 100{\cdot}056 - 63{\cdot}475 \times 30{\cdot}565 = 43{,}660$$

We have now to calculate C_c and D_c, the in-phase and quadrature portions of the current at the supply end of the line. Call this current I_{sc}. The current at the receiver end can be written in the form $P + iQ$.

Equation (4) therefore gives us

$$I_{sc} = (P + iQ)\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right) + EY\left(1 + \frac{YZ}{2 \cdot 3} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4 \cdot 5} \cdots\right)$$

$$\therefore I_{sc} = \underset{C_c}{454{\cdot}78} - i\,\underset{D_c}{54{\cdot}36} = 458{\cdot}02$$

The use of the formulæ proved in Section 2, using the above calculated values of A_c, B_c, C_c, and D_c, gives us the following results :—

Kilowatts at the generators will be

$$= \frac{1}{1{,}000}(A_c C_c + B_c D_c)$$

$$= \frac{1}{1{,}000}(119{,}862 \times 454{\cdot}78 - 43{,}660 \times 54{\cdot}368) = 52{,}137 \text{ kw.}$$

* The amount of reactive current in the line at the receiver end for any load P can be got by substituting this value of P in equation (50) and solving for Q. Where we found the amount of synchronous plant required at no load, we were only taking a particular instance of this where P = 0.

Kilovolt-amperes at the generators

$$= \sqrt{(A' + B')^2 + (C + D)^2} \frac{I}{1,000}$$

or it may be written

$$= \frac{E \sqrt{(C' + D)^2}}{1,000}$$

$$= \frac{127,574 \cdot 458'02}{1,000}$$

$$= 58,431 \text{ k.v.a.}$$

Power factor at generators in per cent

$$= \frac{A C + B D}{E \sqrt{(C + D)^2}} 100 = 89'23\ \%\ \text{lagging}$$

(see below)

The reactive k.v.a. at the generators as before

$$= \frac{I}{1,000}(B C - A D)$$

$$= \frac{I}{1,000}[43,600 \times 454'79 + 110,802 \cdot 54'368] = 26,373$$

As this has a positive sign the reactive current, kilovolt-amperes, and power factor are lagging.

The efficiency of the line alone (excluding synchronous plant)

$$= \frac{E P}{A C + P D} 100 = 85'8\ \%$$

If we wish to get the transmission efficiency, including the synchronous condensers, we have to deduct from the line output the kilowatts required to drive the synchronous plant. Take this as 4 per cent of the capacity of the plant and we get

Efficiency including synchronous plant

$$= \frac{45,302 - \frac{4}{100} 27,620}{52,137} \times 100 = 84'77\ \%$$

We have seen above that Q, the line reactive current at the receiver end $= -63'47$ and is therefore lagging.

Line power factor at receiver end

$$= \frac{P}{\sqrt{P^2 + Q^2}} \times 100$$

$$= \frac{453'02}{\sqrt{[(453'02)^2 + (63'47)^2]}} = 99'03\ \%\ \text{lagging}$$

Examination of Line Carrying 25,000 kw. as the Maximum Load with Constant Voltage.

The foregoing examination of the line in Section 2 when loaded to 45,302 kw. and operated as a constant voltage line discloses the fact that the efficiency is reduced as compared with that of the same line when carrying 25,000 kw. as a varying voltage line. We will therefore investigate the conditions that would obtain if the maximum loading at a constant voltage line is 25,000 kw., and also what voltage will be required between the ends of the line with this loading, and also the amount of synchronous condensers required for this maximum load.

Equation (60) is

$$E_1 = (E_2 + P R_2 + Q X_2)^2 + (P X_2 + Q R_2)^2$$

An examination of the circle diagram in Fig. 5 will make it clear that the minimum amount of synchronous plant (for a given maximum loading) will be required when the conditions are such that the amount of synchronous plant required at no load is equal to the amount of synchronous plant required at the maximum loading. Therefore, in this case, we start with the assumption that the amount of synchronous plant required at no load should be the same as the amount of synchronous plant required at 25,000 kw.

At no load $P = 0$, and Q is an unknown value which we have to determine, and it will be negative in value; therefore put $Q = -Q_0$, Q_0 being the amount of reactive amperes required from the synchronous plant at no load.

Substituting these values for P and Q in equation (49) we get

$$E_1^2 = (E_2 + Q_0 X_2)^2 + (E_2 - Q_0 R_2)^2 \quad . \quad . \quad (61)$$

At 25,000 kw. $P = 250$ and Q will have a value, say, Q_{25}.

From equation (58) we see that the amount of reactive current required from the synchronous plant at any load $P = P \tan \theta + Q$. Therefore at 25,000 kw. the amount required

$$= Q_{25} + P \tan \theta$$
$$= Q_{25} + 250 \times 0'75$$
$$= Q_{25} + 187'5$$

Now this amount of reactive amperes must be equal to that required at no load.

Therefore $$Q = Q_{25} + 187'5$$

Now at 25,000 kw. we have $P = 250$ and $Q = Q_{25} = Q_0 - 187'5$. Substituting these values in equation (49) we get

$$E_1^2 = (E_2 + 250 R_2 - Q X_2 + 187'5 X_2)^2 + (E_2 + Q R_2 - 187'5 R_2 + 250 X_2)^2 \quad . \quad (62)$$

As the voltage E_1 is kept constant, the right-hand side of equation (61) must be equal to the right-hand side of equation (62) as both are equal to E_1^2.

Therefore $$(E_2 + Q_0 X_2)^2 + (E_2 - Q_0 R_2)^2 = (E_2 + 250 R_2 - Q_0 X_2 + 187'5 X_2)^2 + (E_2 + Q R_2 - 187'5 R_2 + 250 X_2)^2$$

Multiplying this out and collecting the terms containing Q_0 we get

$$Q_0 \cdot 4 \times 900'55 + 375)$$
$$= 500 \times 280'58 + 375 \times 900'55 + 62,500 + 35,156'25$$

Therefore $$Q_0 = 144'28$$

Therefore the reactive current required from the synchronous plant at no load

$$= -144'28$$

and at 25,000 kw. $$= +144'28$$

Therefore the amount of synchronous plant required is 14,428 k.v.a., which will be able to give the above amount of lagging reactive current at no load and the above amount of reactive current leading at 25,000 kw.

The voltage at the supply end of the line will be got most easily from equation (61) by substituting the value found above for Q_0. Equation (61) is

$$E_1^2 = (E_2 + Q_0 X_2 + P R_2)^2 + (P X_2 - Q_0 R_2)^2$$

Therefore

$$E_s^2 = (99{,}664 + 144{\cdot}28 \times 100{\cdot}05)^2 + (273{\cdot}60 - 144{\cdot}28 \times 30{\cdot}56)^2$$
$$= 13{,}035{,}800{,}000$$

Therefore $E_s = 114{,}175$

We therefore arrive at the conclusion that, if the line is required to carry 25,000 kw. as the maximum load at constant voltage, the voltage at the supply end of the line will be 114,175 for 100,000 at the receiver end and the capacity of synchronous condensers required will be 14,428 k.v.a.

To complete the solution of the line at 25,000 kw. constant voltage we have again to find the quantities A_c, B_c, C_c, and D_c.

A_c and B_c are respectively the portions of the voltage at the supply end which are in phase and in quadrature with E, the voltage at the receiver end.

As before it will be seen from equation (49) that

$$A_c = E_r + P R_1 - Q X_1$$
$$B_c = E_2 + P X_1 + Q R_1$$

P = 250, and Q can be got as follows :—

The reactive current required from the synchronous plant at any load is $Q + P \tan \theta$.

We know that in this case the reactive current at 25,000 kw. required from the synchronous plant is 144·28.

Therefore $144{\cdot}28 = Q + P \tan \theta = Q + 250 \times 0{\cdot}75$
$= Q + 187{\cdot}75$

Therefore $Q = -43{\cdot}22$

Substituting the values for E_r, E_2, P, Q, R_1 and X_1 in the above equations for A_c and B_c we get

$$A_c = 99{,}664 + 250 \times 30{\cdot}56 + 43{\cdot}22 \times 100{\cdot}05 = 111{,}628$$
$$B_c = 273{\cdot}6 + 250 \times 100{\cdot}05 - 43{\cdot}22 \times 30{\cdot}56 = 23{,}965$$

As before

$$I_{sc} = (P + iQ).\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right) + EY\left(1 + \frac{YZ}{2 \cdot 3} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4 \cdot 5} \cdots\right)$$

and $P + iQ = 250 - i\,43{\cdot}22$

$$\left(\frac{YZ}{2} + \frac{Y^2Z^2}{2 \cdot 3 \cdot 4} \cdots\right) = -0{\cdot}0033554 + i\,0{\cdot}002736$$

$$\therefore I_{sc} = \underset{C_c}{252{\cdot}39} - i\,\underset{D_c}{34{\cdot}73} = 254{\cdot}76$$

Kilowatts at the generators will be

$$= \frac{1}{1{,}000}(A_c C_c + B_c D_c)$$
$$= \frac{1}{1{,}000}(111{,}630 \times 252{\cdot}39 - 23{,}965 \times 34{\cdot}73)$$
$$= 27{,}341 \text{ kw.}$$

Kilovolt-amperes at the generators

$$\frac{1}{1{,}000}\sqrt{(A_c^2 + B_c^2)}\ \sqrt{(C_c + D_c)} = \frac{1}{1{,}000} \times 114{,}175 \times 254{\cdot}76$$
$$= 29{,}087 \text{ k.v.a.}$$

Power factor at the generators

$$= \frac{A_c C_c + B_c D_c}{E_s \sqrt{(C_c^2 + D_c^2)}}\ 100 = 93{\cdot}99 \text{ per cent lagging}$$
(see below)

Reactive kilovolt-amperes at the generators

$$= \frac{1}{1{,}000}(B_c C_c - A_c D_c)$$
$$= \frac{1}{1{,}000}(23{,}965 \times 252{\cdot}39 + 111{,}628 \times 34{\cdot}73)$$
$$= 9{,}925 \text{ k.v.a.}$$

As this is positive, the reactive current at the supply end of the line and the power factor are lagging.

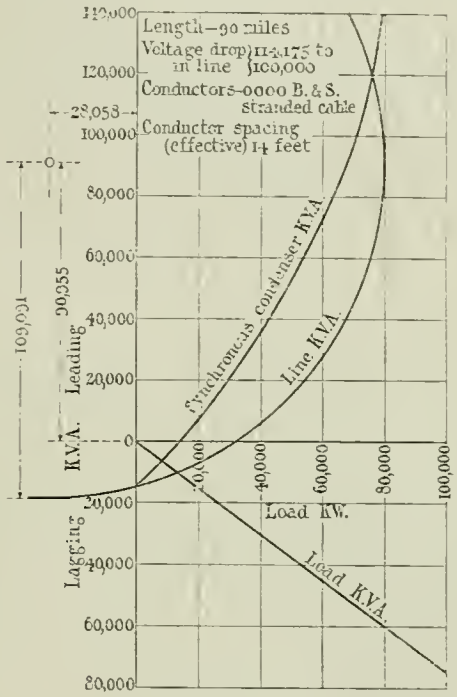

FIG. 6.—Circle diagram for high-tension, constant-voltage, three-phase, 50-period transmission line.

The efficiency of the line alone (excluding synchronous plant)

$$= \frac{E P}{A_c C_c + B_c D_c}\ 100 = 91{\cdot}44\ \%$$

Efficiency, including synchronous plant : The output in this case will be 25,000 less the power taken by the synchronous plant, which we take as 4 per cent.

The efficiency including synchronous plant

$$= \frac{25{,}000 - \frac{4}{100} \times 14{,}428}{27{,}341}\ 100 = 89{\cdot}33\ \%$$

The line power factor at the receiver end where $Q = -43{\cdot}22$

$$= \frac{P}{\sqrt{P^2 + Q^2}}\ 100 = \frac{250}{\sqrt{[(250)^2 + (43{\cdot}22)^2]}}\ 100 = 98{\cdot}54\ \%$$
lagging

We shall also ascertain with the drop from 114,175 to 100,000 what load the line will carry without the synchronous plant.

The synchronous plant has to give, at any load, an amount of reactive current $= Q + P \tan \theta$. When this amount is zero we get $Q + P \tan \theta = 0$.

Therefore $$Q = -P \tan \theta = -0.75\,P$$

Therefore we shall get the load the line will carry without the synchronous plant by making $Q = -P \times 0.75$, and $E = 114,175$ in the equation

$$P^2 + Q^2 - 2P\frac{E_1 R_1 + E_1 X_1}{R_1^2 + X_1^2} - 2Q\frac{E_1 X_1 - E_1 R_1}{R_1^2 + X_1^2} + \frac{E^2 + E_1^2 - E^2}{R_1^2 + X_1^2} = 0$$

or $$1.5625\,P^2 + 1.025\,548\,P - 283,251 = 0$$

$$P = \frac{-1.025\,548 \pm \sqrt{(1.025\,548^2 + 4 \times 1.5625 \times 283,251)}}{2 \times 1.5625}$$

Take the + sign, therefore $P = 13{,}270$, or, converting to kw. we arrive at the conclusion that without synchronous plant this line will transmit 13,279 kw., when the voltage drop is from 114,175 to 100,000.

The circle diagram for the line operating with this drop is shown in Fig. 6.

The amount of synchronous plant required to maintain constant voltage may appear very considerable, and the capital charges on this, combined with the annual cost of current consumed in operating the synchronous plant, might be considered as making the use of synchronous condensers to the extent indicated a non-commercial proposition. Undoubtedly each case would have to be examined on its merits, but where good regulation is necessary, and where the cost of producing current is very low, the use of synchronous apparatus along the lines indicated would undoubtedly be advantageous.

The matter is being considered in these notes from a purely engineering point of view, and no attempt has been made to lay down conditions where synchronous condensers to maintain constant voltage should be used. As before stated, particular cases would have to be analysed in the light of the conditions which obtained as regards the capital cost, generating cost, and regulation conditions, etc.

The following conditions might, however, arise in the case of the line considered in Section 2. In the first instance, it would be necessary on this line to have two separate circuits to guard against insulator or other failures of one of the circuits, and presumably these circuits would be put down as duplicates, so that their combined capacity would be twice 25,000 kw. as varying voltage lines.

When the load grew to 25,000 kw., and assuming that regulation considerations limited the loading of one line to 25,000 kw. as a varying voltage line, it would then be necessary to put down a third circuit, because with the load over 25,000 kw. and one line out of service for any reason, the second line could not carry the whole load. If, however, 14,428 k.v.a. of synchronous plant was provided for each line, 50,000 kw. could be carried at constant voltage on the two circuits with a voltage at the generator end of the lines of 114,175 volts. Assuming one of these circuits broke down, the synchronous plant equal in capacity to 27,029 k.v.a. could be connected to the remaining circuit, and the voltage at the generating station raised to 127,574 volts, when a load of 45,302 kw. could be transmitted over the one good circuit. By raising the voltage a little higher at the generating station, and coupling the full amount of

Summary of Above Results for Line in Section 2.

	As a Varying Voltage Line		As Constant Voltage Line loaded to 25,000 kw.	As Constant Voltage Line, loaded to 45,302 kw.
	No Load	Loaded to 25,000 kw.		
Voltage at receiver end	—	100,000	100,000	100,000
Voltage at supply end for 100,000 at receiver end	90,665	127,574	114,175	127,574
Voltage at receiver end for full load voltage at supply end	128,003	100,000	100,000	100,000
Regulation at supply end for constant receiver volts	—	21·88 %	—	—
Regulation at receiver end for constant supply volts	—	28·003 %	—	—
Current at supply end in total amperes	8·26	300·47	254·79	458·02
Current per wire at supply end = total amps. ÷ √3	4·77	178·7	147·1	264·5
k.v.a. at supply end	823	39,480	29,087	58,431
kw. at supply end	312	28,375	27,341	52,137
Power factor at the supply end	37·0 % leading	71·87 % lagging	93·00 % lagging	89·23 % lagging
Power factor at receiver end	—	80 % lagging	98·54 % lagging	99·03 % lagging
Line efficiency including transformers	—	88·1 %	91·41 %	86·89 %
Station efficiency including losses in synchronous plant	—	—	89·33 %	84·77 %
Amount of synchronous plant at no load	—	—	14,428 k.v.a.	27,029 k.v.a.
Amount of synchronous plant at respective full loads	—	—	14,428 k.v.a.	27,029 k.v.a.
Load carried on line	—	25,000 kw.	25,000 kw.	45,302 kw.

twice 14,428 k.v a. of plant on to the good circuit, the full 50,000 kw. could be transmitted over this circuit. The efficiency of operation during this heavy loading of the one line would be reduced, but the engineering fact stands out that the provision of two 25,000 kw. circuits with synchronous plant for operation as constant voltage lines, would provide the same spare for emergency conditions as the addition of a third line under varying voltage conditions, and would have the additional advantage of providing constant voltage operation, thus eliminating regulation troubles. Further, the cost of providing the synchronous plant would be very much less than that of building an additional tower line, assuming the line to be of not less length or lower voltage than the one in Section 2.

The additional capital expenditure for a third line could be postponed until the load reached the neighbourhood of 50,000 kw., instead of having to undertake this additional cost as soon as the load exceeded 25,000 kw.

In order to make comparison easier between a line operated first as a 25,000 kw. varying voltage line, second as a 25,000 kw. constant-voltage line, and third as a 45,302 kw. constant-voltage line, the various characteristics of these three conditions of loading for the line are given in the table on page 104.

Constant Voltage Transmission.

conditions specified at the supply end of the line.

The above discussion of constant-voltage transmission refers to a case where the conditions are specified at the receiver end. Some variations in the formulæ used are necessary when the conditions are specified at the supply end. These are considered below.

Equation (26) is

$$E = E_s\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2\cdot3\cdot4} \cdots\right) - I_s Z\left(1 + \frac{YZ}{2\cdot3} + \frac{Y^2Z^2}{2\cdot3\cdot4\cdot5} \cdots\right)$$

The first term on the right-hand side could be written in the form $E_{s1} + i\,E_{s2}$.

I_s may be written $P_s + i\,Q_s$

and $Z\left(1 + \frac{YZ}{2\cdot3} + \frac{Y^2Z^2}{2\cdot3\cdot4\cdot5} \cdots\right)$ may be written $R_1 + i\,X_1$

Therefore we can write equation (26) as follows:—

$$E = (E_{s1} + i\,E_{s2}) - (P_s + i\,Q_s)(R_1 + i\,X_1)$$

Multiplying out the above and collecting the terms containing i we get

$$E = (E_{s1} - P_s R_1 + Q_s X_1) + i\,(E_{s2} - P_s X_1 - Q_s R_1)$$

which means that E is made up of two vector portions

$E_{s1} - P_s R_1 + Q_s X_1$ in phase with E_s

and $E_{s2} - P_s X_1 - Q_s R_1$ in quadrature with E_s

Therefore

$$E^2 = (E_{s1} - P_s R_1 + Q_s X_1)^2 + (E_{s2} - P_s X_1 - Q_s R_1)^2 \quad (63)$$

Multiplying out and arranging in descending powers of P and Q we get

$$P_s^2 + Q_s^2 - 2\,P_s\frac{E_{s1}R_1 + E_{s2}X_1}{R_1^2 + X_1^2} + 2\,Q_s\frac{E_{s1}X_1 - E_{s2}R_1}{R_1^2 + X_1^2} + \frac{E_{s1}^2 + E_{s2}^2 - E^2}{R_1^2 + X_1^2} = 0 \quad (64)$$

This is the equation for the circle diagram where the conditions are specified at the supply end. From an earlier section of this paper it will be evident that the data for the circle diagram in this case will be

$$a = \frac{E_s}{1{,}000}\cdot\frac{E_{s1}R_1 + E_{s2}X_1}{R_1^2 + X_1^2}$$

$$b_2 = -\frac{E_s}{1{,}000}\cdot\frac{E_{s1}X_1 - E_{s2}R_1}{R_1^2 + X_1^2}$$

and

$$c_2 = \frac{E_s}{1{,}000}\cdot\frac{E}{\sqrt{(R_1^2 + X_1^2)}}$$

The reactive kilovolt-amperes in the line at the supply end can be either read from the circle diagram or calculated from equation (64) by inserting the value of P_s for any specified load on the generators, and solving for Q_s using only the plus value of the radical.

If Q_s so found is positive the load on the generators is leading, and if negative the load on the generators is lagging.

The kilovolt-amperes at the generators are evidently

$$= E_s\cdot\frac{\sqrt{(P_s^2 + Q_s^2)}}{1{,}000}$$

The power factor at the generators is evidently

$$= \frac{P_s}{\sqrt{(P_s^2 + Q_s^2)}}\,100\ \%$$

Kilowatts at the receiver end. We have seen above that E is made up of $(E_{s1} - P_s R_1 + Q_s X_1)$ in phase with E_s and $(E_{s2} - P_s X_1 - Q_s R_1)$ in quadrature with E_s. Call these respectively F_c and G_c. From equation (27)

$$I = I_s\left(1 + \frac{YZ}{2} + \frac{Y^2Z^2}{2\cdot3\cdot4} \cdots\right) - E_s Y\left(1 + \frac{Y\cdot Z}{2\cdot3} + \frac{Y^2Z^2}{2\cdot3\cdot4\cdot5} \cdots\right)$$

I from this equation is made up of two vector portions Call them H_c and K_c.

Then the kilowatts at the receiver end will be

$$= \frac{1}{1{,}000}(F_c H_c + G_c K_c)$$

The line losses will be the kw. input less the kw. output

$$= \frac{1}{1{,}000}(E_s P_s - F_c H_c - G_c K_c)$$

The kilovolt-amperes at the receiver end will be

$$\frac{E\sqrt{(H_c^2 + K_c^2)}}{1{,}000}$$

Line power factor at receiver end $= \dfrac{F_c H_c + G_c K_c}{E\sqrt{(H_c^2 + K_c^2)}}$

The reactive kilovolt-amperes in the line at the receiver end will be as before

$$\frac{1}{1{,}000}(G_c H_c - F_c K_c)$$

If positive, this represents lagging energy.
If negative, this represents leading energy.
Efficiency of transmission line

$$= \frac{\text{kw. output}}{\text{kw. input}}\,100 = \frac{F_c H_c + G_c K_c}{E_s P_s}\,100\ \%$$

The reactive kilovolt-amperes of synchronous condensers required is got as follows:—

$$\text{The reactive k.v.a. of load} = (\text{kw. load} \times \tan\theta)$$

where θ = angle of lag of load. Add to this the reactive k.v.a. in the line at the receiver end, with due note of the sign of the quantity; the result will give the k.v.a. of the synchronous plant required.

Addendum.

For given voltages at the two ends of the line the *theoretical* maximum load which the line can carry with constant voltage transmission, could be calculated as follows.

If we assume the centre of the circle at a point (a_1, b_1) and the radius of the circle (c_1) then the general equation for the circle could be written thus

$$P^2 + Q^2 - 2a_1P - 2b_1Q + a_1^2 + b_1^2 - c_1^2 = 0, \text{ hence}$$

when P is the maximum $Q = b_1$, and $P = c_1 + a_1$.

It will be seen by an examination of the circle diagrams contained in this paper that a_1 has a negative value in the cases considered, and that $P = c_1 + a_1$ corresponds to the furthest point toward the right of the circle, or the ellipse.

This possible maximum load is of little interest except from a theoretical point of view because, except in the case of lines with very large conductors, the amount of synchronous plant required increases very rapidly as the maximum is reached, and the efficiency of transmission becomes very poor.

Section 6.

Illustrative Example: 130,000-volt Line.

The conditions assumed are as follows:—

Power to be delivered	18,000 kw.
Phase and frequency	3 phase, 25 periods
Voltage at receiver end of line ...	130,000
Power factor of load	80 per cent
Size of each conductor	350 000 c.r. mils.
Effective spacing of conductors ...	16 ft.
Reactance of transformers, coils, etc., at each end of line	say, 6 per cent
Resistance of transformers, coils, etc., at each end of line	say, 1 per cent
Length of line	380 miles

$$\text{Total load current} = \frac{18,000 \times 1,000}{130\,000 \times 0{\cdot}8} = 173$$

Therefore, current in phase with receiver voltage

$$= 173 \times 0{\cdot}8 = 138{\cdot}4$$

and current in quadrature with receiver voltage

$$= 173 \times 0{\cdot}6 = 103{\cdot}8$$

Summary of Results obtained for 380-mile 130,000-volt Line.

	Loaded to 18,000 kw. as Varying Voltage Line		Loaded to 18,000 kw. as Constant Voltage Line	Loaded to 32,894 kw. as Constant Voltage Line
	No Load	Full Load		
Voltage at receiver end for constant supply voltage ..	106,068	130,000	130,000	130,000
Regulation at receiver end for constant supply voltage as percentage of E	—	28·4 %	—	—
Voltage at supply end for 130,000 at receiver end ..	120,245	154,439	138,212	154,439
Regulation at supply end for constant receiver volts ..	—	22·14 %	—	—
k.v.a. at supply end	10,771	20,338	20,082	37,600
kw. at supply end	422	20,056	19,765	37,577
Power factor at supply end	3·9 % leading	98·6 % lagging	95·56 % leading	99·76 % lagging
Power factor at receiver end	—	80 % lagging	98·98 % lagging	99·3 % lagging
Efficiency of line	—	89·7 %	91·07 %	88·73 %
Efficiency of transmission	—	—	88·85 %	84·52 %
Synchronous plant required at no load	—	—	10,941 k.v.a.	20,821 k.v.a.
Synchronous plant required at full load	—	—	10,941 k.v.a.	20,821 k.v.a.

Total resistance of one line, including transformers, etc.,

$$= 61{\cdot}75 + 15 = 76{\cdot}75 \text{ ohms}$$

Total reactance of one line, including transformers, etc.,

$$= 127{\cdot}3 + 90 = 217{\cdot}3$$

Therefore $Z = 76{\cdot}75 + i\,217{\cdot}3$

Admittance due to line proper

$$= 0 + i\,0{\cdot}0008398$$

Admittance due to transformers, etc.,

$$= 0{\cdot}0000133 - i\,0{\cdot}000133$$

Therefore total admittance

$$Y = 0{\cdot}0000133 + i\,0{\cdot}0007068$$

Figs. 7 and 8 show the circle diagrams for the two conditions of constant voltage loading referred to in the above schedule.

Although not directly connected with the actual calculations of the two lines considered in these notes, the following comments may be of some interest.

It will be noted that the charging kilovolt-amperes for the 90 mile line is relatively small, being 823 k.v.a. This is due to the fact that the line capacity current which is

leading is balanced to a great extent by the magnetizing current of the transformers which is lagging, and by the lagging reactive k.v.a. set up in the line itself, due to the current which furnishes the magnetizing energy and no load losses to the transformers flowing through the line reactance.

In the case of the 380-mile line, the capacity is high, and even after deducting the magnetizing current for the transformers, etc., there still remains a balance, which requires 10,771 k.v.a. of generating plant to be connected to the line at no load, in order to charge the line and maintain 130,000 volts at no load.

It will be noted that on the 90-mile line loaded to 25,000 kw. as a varying voltage line the power factor at the generators is 71·87 per cent lagging, for 80 per cent

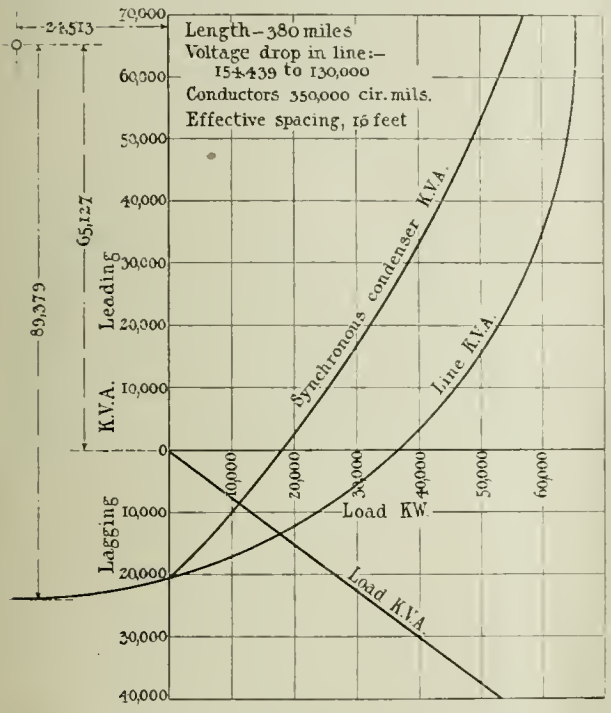

Fig. 7.—Circle diagram for high-tension, constant-voltage, three-phase, 25-period transmission line.

power-factor load at the receiver end. In this case the capacity current of the line is not sufficient to balance the reactive kilovolt-amperes of the line when carrying the full-load current, so that the power factor is worse at the generators than at the receiver end of the line, though better than it would have been had capacity not existed. In the case of the 380-mile line, however, operated as a varying voltage line and loaded to 18,000 kw. it will be seen that the power factor at the generators is 98·6 per cent lagging as against the 80 per cent lagging of the load at the receiver end. In this case the line capacity is so great that it practically balances the reactive kilovolt-amperes of the load and the line, and therefore very materially improves the power factor for the generators.

It will therefore be seen that although the line capacity may be regarded as a drawback under no-load conditions, it has distinct advantages at full load, in that it creates better load conditions for the generators and for a given load reduces the generator k.v.a. capacity below what would be required if the line had no capacity. For example, in the case of the 380-mile line delivering 18,000 kw. at 0·8 power factor (i.e. delivering a load of 22,500 k.v.a.) the generator k.v.a. necessary is 20,388 only, being actually less than that of the load.

In the case of the 90-mile line delivering 25,000 kw. 0·8 power factor (or 31,250 k.v.a.) the generator k.v.a. required is 39,480. This is less than would be needed without line capacity, but as this capacity is small the reduction is not nearly so marked as in the case of the longer line with greater capacity.

On the assumption that the lines considered in these notes are run as varying voltage lines, it would be necessary, in order to maintain constant voltage at the receiver

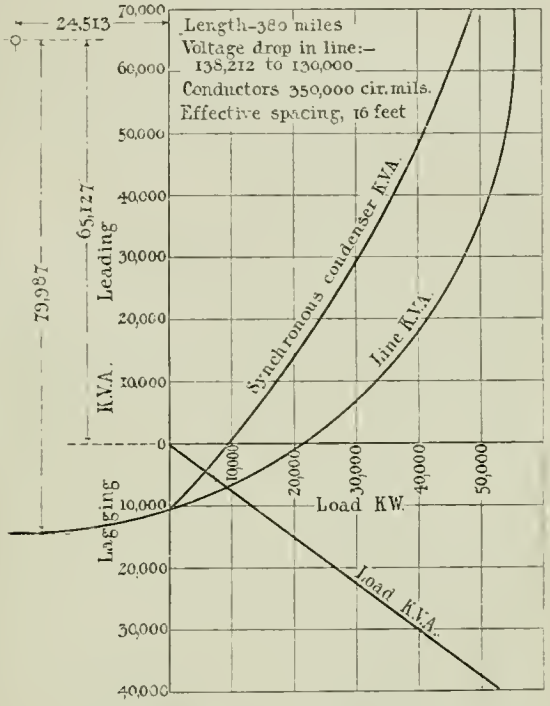

Fig. 8.—Circle diagram for high-tension, constant-voltage, three-phase, 25-period transmission line.

end between no load and full load, to vary the voltage at the generator end of the 90-mile line 21·88 per cent, and in the case of the 380-mile line 22·14 per cent of the full-load generator volts.

In ordinary conditions of working the load would probably not be changing very rapidly and the voltage regulation could probably be taken care of by hand regulation of the generator fields, as soon as sufficient experience has been gained in operating the lines to ascertain what voltage at the generating station would be required for various loads. Load and voltage curves at the generator station could be plotted, and the generator volts so regulated that approximately constant voltage would be maintained at the receiver end. The operating conditions would determine whether this was possible, but it is easy to conceive loads such as that taken by electric furnaces, rolling mills, etc., which would make it impossible for satisfactory hand regulation of the generator volts to be

carried out even with induction regulators installed on the feeders at the receiving substation. In these cases specially adjusted voltage regulators on the generators might do the work, but in very long lines such as the 380-mile line it would almost certainly be found, in practice, impossible to give satisfactory service without the addition of sufficient synchronous plant to obtain constant voltage transmission.

Further, for the maximum voltage drop between the ends of the line, as limited by permissible regulation, it would probably be found impossible, in the case of very long lines, to transmit sufficient power as varying voltage lines to make them commercial propositions. The increased loading for the same drop between the ends of the line when operated for constant voltage transmission would make many lines profitable which otherwise would not be so.

In the case of varying voltage lines there are conditions arising in practice due to faults, which would make the rise in voltage at the receiver end very much greater than that calculated, and which point to the provision of specially designed generators to assist in meeting the difficulties which would arise.

Take the case of the 380-mile line operating as a varying voltage line, and carrying as a maximum load 18,000 kw. The load is assumed to have a power factor of 80 per cent, but due to the line capacity the power factor at the generating end is 0·86 per cent lagging at full load. Assuming the line to be delivering 18,000 kw. with generators loaded to 20,388 k.v.a., and some circumstances arising which trip the line breakers at the *receiver* end, the line load would change from 18,000 kw. to zero. Due to the charging current of the line remaining on the generators, we get the loading of the generators changing from 20,388 k.v.a. at 0·86 per cent lagging to 10,771 k.v.a. (the charging k.v.a.) at 3·9 per cent power factor leading. Under the loaded conditions specified the generators would be taking a little more than normal excitation from their exciters to deal with the lagging load which they were carrying, but when the circuit breakers open in the manner indicated, the power factor at the generators would suddenly change to a very low leading value, and the high charging current making up the 10,771 k.v.a. required for charging the line, being almost in quadrature leading, would tend to raise the voltage at the generators very considerably. We see, therefore, that not only would the receiver voltage rise due to the load coming off, but there would be an additional very great increase due to the sudden increase in the generator voltage.

Neglecting altogether the effect of any surging which would occur in the line, and which in itself would cause momentarily considerably increased voltage, we see that the receiver voltage would rise under these special conditions far above the 186,098 volts calculated at no load for constant generator volts. Without knowing the generator design it is impossible to say just what this voltage would be, but it is safe to assume that the receiver voltage would rise to the neighbourhood of 200,000 at least.

Take another condition which might arise in actual practice. At no load the generator power factor is 3·7 per cent leading and at full load of 18,000 kw the power factor is 0·86 per cent lagging. At loads up to near normal full load therefore, the generator power factor would be leading, and at relatively low loads would be leading very considerably. The resulting currents in the generator would therefore assist the excitation taken from the exciters, and would tend to raise the generator voltage. Consequently, for constant receiver volts it would be necessary, when the generators were carrying leading current, to draw from the exciters only a very small amount of exciting current, especially at low loads. If under light load conditions something were to take place on the line which caused the line breakers at the generator end of the line to open, not only would the load be cut off, but the line charging current would also be cut off, and the generators would be left running with only the low excitation taken from the exciters. There would therefore, under these conditions, be a very large drop in voltage on the station busbars, and under certain conditions this drop would be so great that the station auxiliaries, if driven from the main busbars, might shut down.

Three important conclusions appear to stand out as the result of the above considerations which apply with special force to long lines of high capacity.

(1) The generators should be so designed that they would respond sluggishly to sudden changes in circuit conditions, so that there would not be any great change in the generator voltage before any voltage regulators installed could alter the excitation to take care of the new conditions.
(2) The voltage regulators in use at the generating station should have a very broad range of control.
(3) Important station auxiliaries, if electrically driven, should be operated from small units independent of the main generating sets or, as an alternative should be steam driven.

Section 7.

Tables of Line Data.

The following tables are attached as they are necessary for the solution of lines by the methods set out in these notes.

Table 1.—Corona limits of voltage.

The size of conductors chosen should be such that the limits set out in this table are not exceeded in ordinary service.

Table 2.—Resistance of copper wire and cable.
Table 3.—Resistance of aluminum cable.
Table 4.—Reactance of wire, 25 cycles.
Table 5.—Reactance of cable, 25 cycles.
Table 6.—Capacity susceptance of wire, 25 cycles.
Table 7.—Capacity susceptance of cable, 25 cycles.

It will be noted that the cable and wire sizes mentioned in these tables are American standards. It is a matter of regret to British engineers outside the United Kingdom that British cable makers and engineers have not tabulated, and published, corresponding data for British standard wires and cables.

It is only natural that colonial or foreign corporations, and engineers, installing high-tension transmission schemes should base their preliminary investigations and calcula-

tions on American wires, as data for these only is available. This reacts unfavourably on British firms seeking the interests of the British electrical engineering industry, the Institution should take the necessary steps in conjunction

TABLE I.

Corona Limit of Voltage.

Kilovolts at sea level for three-phase lines.

Cables		Spacing, in Feet					
B. & S. or Circular Mils	Diameter in Inches	8	10	12	14	16	20
0	0·374	95	98	102	104	106	109
00	0·420	104	108	111	114	117	121
000	0·470	114	118	121	124	127	132
0,000	0·530	125	130	135	138	141	146
250,000	0·590	138	144	149	152	156	161
300,000	0·620	—	151	156	161	165	171
350,000	0·679	—	161	166	170	175	180
400,000	0·728	—	171	176	180	185	192
450,000	0·770	—	178	184	190	194	200
500,000	0·818	—	188	194	199	205	210
800,000	1·034	—	—	234	241	244	256

Altitude Correction Factor.

Altitude, in Feet	Correction Factor	Altitude, in Feet	Correction Factor
0	1·00	5,000	0·82
500	0·98	6,000	0·79
1,000	0·96	7,000	0·77
1,500	0·94	8,000	0·74
2,000	0·92	9,000	0·71
2,500	0·91	10,000	0·68
3,000	0·89	12,000	0·63
4,000	0·86	14,000	0·58

To find the voltage for any altitude, multiply the voltage found in the table by the corresponding correction factor. For single-phase or two-phase, find the three-phase voltage above and multiply by 1·16.

contract for line construction and other electrical work in connection with such schemes.

The author therefore makes the suggestion that, in the with cable manufacturers in Great Britain, to ensure the preparation and publication as early as possible of corresponding data for British wires and cables.

TABLE 2.—*Resistance of Copper Wire and Cable.*

Data assumed. Temperature, 25° C. (68° F.).
Conductivity of hard drawn copper, 97·3 per cent of the annealed copper standard.
Increase in resistance of cables due to spiraling, 1 per cent.

Copper Wire.

B. & S.	Circular Mils	Diameter in Inches	Number of Wires assumed	Resistance, Ohms per Mile				
				Direct Current	25 Cycles	Increase	60 Cycles	Increase
						Per cent		Per cent
0000	211,600	0·4600	—	0·2055	0·2057	0·08	0·2067	0·44
000	167,800	0·4096	—	0·3348	0·3350	0·05	0·3358	0·27
00	133,100	0·3648	—	0·4221	0·4223	0·03	0·4229	0·17
0	105,500	0·3249	—	0·5326	0·5327	0·02	0·5331	0·11
1	83,690	0·2893	—	0·6714	0·6714	0·01	0·6718	0·07
2	66,370	0·2576	—	0·8466	0·8466	0·01	0·8469	0·04
3	52,630	0·2294	—	1·068	1·068	—	1·068	0·03
4	41,740	0·2043	—	1·346	1·346	—	1·346	0·02
5	33,100	0·1819	—	1·697	1·697	—	1·698	0·01
6	26,250	0·1620	—	2·140	2·140	—	2·140	0·01
7	20,820	0·1443	—	2·699	2·699	—	2·699	—
8	16,510	0·1285	—	3·403	3·403	—	3·403	—

Copper Cable.

B. & S.	Circular Mils	Diameter in Inches	Number of Wires assumed	Resistance, Ohms per Mile				
				Direct Current	25 Cycles	Increase	60 Cycles	Increase
						Per cent		Per cent
—	500,000	0·8111	19	0·1135	0·1140	0·41	0·1162	2·34
—	450,000	0·7805	19	0·1261	0·1265	0·33	0·1285	1·90
—	400,000	0·7255	19	0·1419	0·1422	0·20	0·1440	1·50
—	350,000	0·6786	19	0·1621	0·1625	0·20	0·1640	1·16
—	300,000	0·6211	7	0·1892	0·1894	0·15	0·1908	0·85
—	250,000	0·5660	7	0·2270	0·2272	0·10	0·2284	0·60
0000	211,000	0·5216	7	0·2682	0·2684	0·07	0·2693	0·43
000	167,800	0·4645	7	0·3382	0·3384	0·05	0·3391	0·27
00	133,100	0·4137	7	0·4264	0·4265	0·03	0·4271	0·17
0	105,500	0·3683	7	0·5379	0·5380	0·02	0·5385	0·11
1	83,690	0·3280	7	0·6781	0·6782	0·01	0·6785	0·07
2	66,370	0·2921	7	0·8550	0·8551	0·01	0·8554	0·04
3	52,630	0·2601	7	1·078	1·078	—	1·078	0·03
4	41,740	0·2317	7	1·360	1·360	—	1·360	0·02

Temperature Coefficients of Copper.—For different initial temperatures and different conductivities

Conductivity Matthiessen's Standard	Percent Conductivity	α_0	α_{10}	α_{15}	α_{20}	α_{25}	α_{30}
100·0	98	0·00425	0·00381	0·00374	0·00367	0·00361	0·00336
101·0	99	0·00430	0·00386	0·00378	0·00371	0·00364	0·00340
102·0	98	0·00414	0·00380	0·00382	0·00375	0·00368	0·00343
100·0	97·3	0·00415	0·00361	0·00383	0·00376	0·00369	0·00344
98·04	96	0·00418	0·00364	0·00386	0·00379	0·00372	0·00346
95·57	96	0·00423	0·00368	0·00390	0·00383	0·00375	0·00349
94·0000	100	0·00428	0·00402	0·00391	0·00386	0·00379	0·00352
91·91	101	0·00432	0·00406	0·00398	0·00391	0·00383	0·00355

Here $R_t = R_0(1 + \alpha_0 t)$, where R_t is the resistance at any temperature t deg. C., and R_0 is the resistance at any initial temperature 0° C. deg. C. From Appendix I., *Standardization Rules* of the *A.I.E.E.*, June 28, 1911.

TABLE 3.—*Resistance of Aluminium Cable.*

Data assumed : Temperature, 20° C. (68° F.).
Conductivity of hard drawn aluminium, 60·86 per cent of the annealed copper standard.
Increase of resistance of cables due to spiralling, 1 per cent.

Aluminium Cable.

B. & S.	Circular Mils	Diameter (2ρ), Inches	Number of Wires assumed	Resistance, Ohms per Mile				
				Direct Current	25 Cycles	Increase	60 Cycles	Increase
						Per cent		Per cent
—	556,500	0·8557	19	0·1630	0·1634	0·20	0·1649	1·14
—	477,000	0·7922	19	0·1902	0·1905	0·15	0·1918	0·84
—	397,500	0·7232	19	0·2282	0·2285	0·10	0·2296	0·59
—	336,420	0·6577	7	0·2697	0·2699	0·07	0·2708	0·42
—	266,800	0·5857	7	0·3401	0·3402	0·05	0·3410	0·27
0000	211,600	0·5216	7	0·4288	0·4289	0·03	0·4295	0·17
000	167,800	0·4645	7	0·5407	0·5407	0·02	0·5412	0·10
00	133,100	0·4137	7	0·6816	0·6817	0·01	0·6821	0·07
0	105,500	0·3683	7	0·8600	0·8600	0·01	0·8603	0·04
1	83,690	0·3280	7	1·084	1·084	—	1·084	0·03
2	66,370	0·2921	7	1·367	1·367	—	1·367	0·02
3	52,630	0·2601	7	1·724	1·724	—	1·724	0·01
4	41,740	0·2317	7	2·174	2·174	—	2·174	0·01

Temperature coefficient of aluminium at 20° C, $a_{23}=0·0039$.

TABLE 4.—*Reactance of Wire, 25 Cycles.*

$x=2\pi f\times 741·1\log_{10}\frac{s}{0·779\,\rho}\times 10^{-6}$ ohms per mile. ρ=radius of wire. s=spacing.

For three-phase irregular spacing use $s=\sqrt[3]{(a\,b\,c)}$. For three-phase regular flat spacing use $s=1·26\,a$.
For a two-phase line the spacing is the average distance between centres of conductors of the same phase.

B. & S.	No. 0000	No. 000	No. 00	No. 0	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	
Circ. Mils	211,600	167,800	133,100	105,500	83,690	66,370	52,630	41,740	33,100	26,250	20,820	16,510	Spacing
Diam. (2ρ), In.	0·4600	0·4096	0·3648	0·3249	0·2893	0·2576	0·2294	0·2043	0·1819	0·1620	0·1443	0·1285	
Spacing (s), Feet													
1	0·213	0·219	0·224	0·230	0·236	0·242	0·248	0·254	0·259	0·265	0·271	0·277	1
1·5	0·233	0·239	0·245	0·251	0·256	0·262	0·268	0·274	0·280	0·286	0·292	0·298	1·5
2	0·248	0·254	0·259	0·265	0·271	0·277	0·283	0·289	0·295	0·300	0·306	0·312	2
2·5	0·259	0·265	0·271	0·276	0·282	0·288	0·294	0·300	0·306	0·312	0·318	0·323	2·5
3	0·268	0·274	0·280	0·286	0·292	0·297	0·303	0·309	0·315	0·321	0·327	0·333	3
3·5	0·276	0·282	0·288	0·293	0·299	0·305	0·311	0·317	0·323	0·329	0·335	0·340	3·5
4	0·283	0·289	0·294	0·300	0·306	0·312	0·318	0·324	0·330	0·335	0·341	0·347	4
4·5	0·289	0·295	0·300	0·306	0·312	0·318	0·324	0·330	0·335	0·341	0·347	0·353	4·5
5	0·294	0·300	0·306	0·311	0·317	0·323	0·329	0·335	0·341	0·347	0·353	0·358	5
6	0·303	0·309	0·315	0·321	0·327	0·333	0·338	0·344	0·350	0·356	0·362	0·368	6
7	0·311	0·317	0·323	0·329	0·334	0·340	0·346	0·352	0·358	0·364	0·370	0·375	7
8	0·318	0·324	0·330	0·336	0·341	0·347	0·353	0·359	0·365	0·370	0·376	0·382	8
9	0·324	0·330	0·335	0·341	0·347	0·353	0·359	0·365	0·370	0·376	0·382	0·388	9
10	0·329	0·335	0·341	0·347	0·352	0·358	0·364	0·370	0·376	0·382	0·388	0·394	10
11	0·334	0·340	0·346	0·351	0·357	0·363	0·369	0·375	0·381	0·387	0·392	0·398	11
12	0·338	0·344	0·350	0·356	0·362	0·368	0·374	0·379	0·385	0·391	0·397	0·403	12
13	0·342	0·348	0·354	0·360	0·366	0·372	0·378	0·383	0·389	0·395	0·401	0·407	13
14	0·346	0·352	0·358	0·364	0·369	0·375	0·381	0·387	0·393	0·399	0·405	0·411	14
15	0·350	0·356	0·361	0·367	0·373	0·379	0·385	0·391	0·396	0·402	0·408	0·414	15
16	0·353	0·359	0·365	0·370	0·376	0·382	0·388	0·394	0·400	0·406	0·411	0·417	16
18	0·359	0·365	0·371	0·376	0·382	0·388	0·394	0·400	0·406	0·411	0·417	0·423	18
20	0·364	0·370	0·376	0·382	0·388	0·394	0·399	0·405	0·411	0·417	0·422	0·428	20

TABLE 5

Reactance of Cable, 25 Cycles.

$x = 2\pi f \times 741 \times 1 \log_{\varepsilon} \frac{s}{0{\cdot}728\,\varrho} \times 10^{-9}$ ohms per mile for a 7 wire stranded cable $\left[\text{Use } \log_{10} \frac{s}{0{\cdot}758\,\varrho} \text{ for 19 wires}\right]$

ϱ = maximum radius of cable

s = spacing

For three phase irregular spacing use $s = \sqrt[3]{abc}$

For three phase regular flat spacing use $s = 1{\cdot}26\,a$

For a two phase line the spacing is the average distance between centres of conductors of the same phase.

	Sizes for Copper Cables						Sizes for Aluminium Cables					
Circular Mils	500,000	450,000	400,000	350,000	300,000	250,000	550,500	477,000	397,500	336,420	266,800	
Number of Wires in Conductor	19	19	19	19	7	7	19	19	19	7	7	Spacing
Diameter of Conductor	0·8111	0·7660	0·7255	0·6781	0·6211	0·5569	0·8557	0·7922	0·7232	0·6577	0·5557	
Spacing in Feet												
1	0·185	0·188	0·191	0·193	0·201	0·205	0·183	0·186	0·191	0·198	0·204	1
1·5	0·206	0·208	0·211	0·215	0·221	0·226	0·203	0·206	0·211	0·218	0·224	1·5
2	0·220	0·223	0·226	0·229	0·236	0·240	0·218	0·221	0·226	0·233	0·239	2
2·5	0·232	0·234	0·237	0·241	0·247	0·252	0·229	0·233	0·237	0·244	0·250	2·5
3	0·241	0·244	0·246	0·250	0·256	0·261	0·238	0·242	0·246	0·253	0·259	3
3·5	0·249	0·251	0·254	0·258	0·264	0·269	0·246	0·249	0·254	0·261	0·267	3·5
4	0·255	0·258	0·261	0·264	0·271	0·275	0·253	0·256	0·261	0·268	0·274	4
4·5	0·261	0·264	0·267	0·270	0·277	0·281	0·259	0·262	0·267	0·274	0·280	4·5
5	0·267	0·269	0·272	0·276	0·282	0·287	0·264	0·268	0·272	0·279	0·285	5
6	0·276	0·279	0·281	0·285	0·291	0·296	0·273	0·277	0·282	0·288	0·294	6
7	0·284	0·286	0·289	0·293	0·299	0·304	0·281	0·285	0·289	0·296	0·302	7
8	0·290	0·293	0·296	0·299	0·306	0·311	0·288	0·292	0·296	0·303	0·309	8
9	0·296	0·299	0·302	0·305	0·312	0·316	0·294	0·297	0·302	0·309	0·315	9
10	0·301	0·304	0·307	0·311	0·317	0·322	0·299	0·303	0·308	0·314	0·320	10
11	0·306	0·309	0·312	0·316	0·322	0·327	0·304	0·308	0·312	0·319	0·325	11
12	0·311	0·314	0·317	0·320	0·327	0·331	0·308	0·312	0·317	0·324	0·330	12
13	0·315	0·318	0·321	0·324	0·331	0·335	0·312	0·316	0·321	0·328	0·334	13
14	0·319	0·321	0·325	0·328	0·334	0·339	0·316	0·320	0·325	0·331	0·337	14
15	0·322	0·325	0·328	0·331	0·338	0·342	0·320	0·323	0·328	0·335	0·341	15
16	0·326	0·328	0·331	0·335	0·341	0·346	0·323	0·327	0·331	0·338	0·344	16
18	0·331	0·334	0·337	0·341	0·347	0·352	0·329	0·332	0·337	0·344	0·350	18
20	0·337	0·340	0·342	0·346	0·352	0·357	0·334	0·338	0·343	0·349	0·356	20

TABLE 5—*continued.*

Reactance of Cable, 25 Cycles—continued.

For three-phase irregular spacing use $s = \sqrt[3]{(a\,b\,c)}$.
For three-phase regular flat spacing use $s = 1{\cdot}26\,a$.
For a two-phase line the spacing is the average distance between centres of conductors of the same phase.

Sizes for both Copper and Aluminium Cables.

B. & S.	No. 0000	No. 000	No. 00	No. 0	No. 1	No. 2	No. 3	No. 4	
Circular Mils	211,600	167,800	133,100	105,500	83,690	66,370	52,630	41,740	
Number of Wires assumed	7	7	7	7	7	7	7	7	Spacing
Diameter (2ρ), Inches	0·5216	0·4645	0·4137	0·3683	0·3280	0·2921	0·2601	0·2317	
Spacing (s), Feet									
1	0·210	0·215	0·221	0·227	0·233	0·239	0·245	0·251	1
1·5	0·230	0·236	0·242	0·248	0·254	0·259	0·265	0·271	1·5
2	0·245	0·251	0·256	0·262	0·268	0·274	0·280	0·286	2
2·5	0·256	0·262	0·268	0·274	0·279	0·285	0·291	0·297	2·5
3	0·265	0·271	0·277	0·283	0·289	0·294	0·300	0·306	3
3·5	0·273	0·279	0·285	0·290	0·296	0·302	0·308	0·314	3·5
4	0·280	0·286	0·291	0·297	0·303	0·309	0·315	0·321	4
4·5	0·286	0·292	0·297	0·303	0·309	0·315	0·321	0·327	4·5
5	0·291	0·297	0·303	0·309	0·315	0·320	0·326	0·332	5
6	0·300	0·306	0·312	0·318	0·324	0·330	0·335	0·341	6
7	0·308	0·314	0·320	0·326	0·331	0·337	0·343	0·349	7
8	0·315	0·321	0·326	0·332	0·338	0·344	0·350	0·356	8
9	0·321	0·326	0·332	0·338	0·344	0·350	0·356	0·362	9
10	0·326	0·332	0·338	0·344	0·350	0·355	0·361	0·367	10
11	0·331	0·337	0·343	0·348	0·354	0·360	0·366	0·372	11
12	0·335	0·341	0·347	0·353	0·359	0·365	0·371	0·376	12
13	0·339	0·345	0·351	0·357	0·363	0·369	0·375	0·380	13
14	0·343	0·349	0·355	0·361	0·367	0·372	0·378	0·384	14
15	0·347	0·352	0·358	0·364	0·370	0·376	0·382	0·388	15
16	0·350	0·356	0·361	0·367	0·373	0·379	0·385	0·391	16
18	0·356	0·362	0·367	0·373	0·379	0·385	0·391	0·397	18
20	0·361	0·367	0·373	0·379	0·385	0·390	0·396	0·402	20

TABLE 6.

Capacity Susceptance of Wire, 25 Cycles.

b [approx] $= 2\pi f \times 38{\cdot}83 \times 10^{-9}$ mhos per mile.

$$\log_{10}\left(\frac{s}{\rho}\right)$$

ρ = radius of wire.

s = spacing

For three phase irregular spacing use $s = \sqrt[3]{(abc)}$.

For three phase regular flat spacing use $s = 1{\cdot}26\,a$.

For a two phase line the spacing is the average distance between centres of conductors of the same phase.

B. & S.	No. 000	No. 00	No. 0	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	
Circular Mils	211,600	167,800	133,100	105,500	83,690	66,370	52,630	41,740	33,100	26,250	20,820	16,510	Spacing
Diameter, Inches	0·4600	0·4096	0·3648	0·3249	0·2893	0·2576	0·2294	0·2043	0·1819	0·1620	0·1443	0·1285	
Spacing, Feet	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{-1}$	
1	3·55	3·45	3·35	3·20	3·18	3·10	3·02	2·95	2·88	2·81	2·75	2·69	1
1·5	3·22	3·14	3·06	2·98	2·91	2·84	2·78	2·72	2·66	2·60	2·54	2·49	1·5
2	3·02	2·95	2·88	2·81	2·75	2·69	2·63	2·57	2·52	2·47	2·42	2·37	2
2·5	2·88	2·82	2·75	2·69	2·63	2·58	2·52	2·47	2·42	2·38	2·33	2·29	2·5
3	2·78	2·72	2·66	2·60	2·55	2·49	2·44	2·40	2·35	2·30	2·26	2·22	3
3·5	2·70	2·64	2·58	2·53	2·48	2·43	2·38	2·33	2·29	2·25	2·21	2·17	3·5
4	2·63	2·57	2·52	2·47	2·42	2·37	2·33	2·28	2·24	2·20	2·16	2·12	4
4·5	2·57	2·52	2·47	2·42	2·37	2·33	2·28	2·24	2·20	2·16	2·12	2·09	4·5
5	2·52	2·47	2·42	2·38	2·33	2·29	2·24	2·20	2·16	2·13	2·09	2·05	5
6	2·44	2·40	2·35	2·30	2·26	2·22	2·18	2·15	2·10	2·07	2·03	2·00	6
7	2·38	2·34	2·29	2·25	2·21	2·17	2·13	2·09	2·06	2·02	1·99	1·96	7
8	2·33	2·28	2·24	2·20	2·16	2·12	2·09	2·05	2·02	1·98	1·95	1·92	8
9	2·28	2·24	2·20	2·16	2·12	2·09	2·05	2·02	1·98	1·95	1·92	1·89	9
10	2·24	2·20	2·16	2·13	2·09	2·05	2·02	1·99	1·96	1·92	1·89	1·86	10
11	2·21	2·17	2·13	2·10	2·06	2·03	1·99	1·96	1·93	1·90	1·87	1·84	11
12	2·18	2·14	2·11	2·07	2·03	2·00	1·97	1·94	1·91	1·88	1·85	1·82	12
13	2·15	2·12	2·08	2·04	2·01	1·98	1·95	1·92	1·89	1·86	1·83	1·80	13
14	2·13	2·09	2·06	2·02	1·99	1·96	1·93	1·90	1·87	1·84	1·81	1·79	14
15	2·11	2·07	2·04	2·00	1·97	1·94	1·91	1·88	1·85	1·82	1·80	1·77	15
16	2·09	2·05	2·02	1·99	1·95	1·92	1·89	1·86	1·84	1·81	1·78	1·75	16
18	2·05	2·02	1·99	1·95	1·92	1·89	1·86	1·83	1·81	1·78	1·75	1·73	18
20	2·02	1·99	1·96	1·92	1·89	1·87	1·84	1·81	1·78	1·76	1·73	1·71	20

TABLE 7.

Capacity Susceptance of Cable, 25 Cycles.

$$b\ (\text{approx.}) = \frac{2\pi f \times 38{\cdot}83 \times 10^{-9}}{\log_{10}\left(\frac{s}{\varrho} - \frac{\varrho}{s}\right)} \text{ mhos per mile.}$$

ϱ = maximum radius of cable.
s = spacing.
For three-phase irregular spacing use $s = \sqrt[3]{(a\,b\,c)}$.
For three-phase regular flat spacing use $s = 1{\cdot}26\,a$.
For a two-phase line the spacing is the average distance between centres of conductors of the same phase.

	Sizes for Copper Cables					Sizes for Aluminium Cables					
Circular Mils	500,000	450,000	400,000	350,000	300,000	250,000	556,500	477,000	397,500	336,420	266,800	
Number of Wires assumed	19	19	19	19	7	7	19	19	19	7	7	Spacing
Diameter (2ϱ), Inches	0·8111	0·7695	0·7255	0·6786	0·6211	0·5669	0·8557	0·7922	0·7232	0·6577	0·5857	
Spacing (s), Feet	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	
1	4·15	4·08	4·01	3·94	3·84	3·75	4·21	4·12	4·01	3·91	3·78	1
1·5	3·70	3·65	3·60	3·54	3·46	3·38	3·76	3·68	3·60	3·51	3·41	1·5
2	3·44	3·40	3·35	3·30	3·23	3·16	3·49	3·42	3·35	3·27	3·19	2
2·5	3·26	3·23	3·18	3·13	3·07	3·01	3·31	3·25	3·18	3·11	3·03	2·5
3	3·13	3·10	3·06	3·01	2·95	2·90	3·17	3·11	3·05	2·99	2·92	3
3·5	3·03	2·99	2·95	2·91	2·86	2·81	3·06	3·01	2·95	2·90	2·83	3·5
4	2·94	2·91	2·87	2·84	2·79	2·74	2·98	2·93	2·87	2·82	2·75	4
4·5	2·87	2·84	2·81	2·77	2·72	2·68	2·90	2·86	2·81	2·75	2·69	4·5
5	2·81	2·78	2·75	2·71	2·67	2·62	2·84	2·80	2·75	2·70	2·64	5
6	2·71	2·68	2·65	2·62	2·58	2·54	2·74	2·70	2·65	2·61	2·55	6
7	2·63	2·61	2·58	2·55	2·51	2·47	2·66	2·62	2·58	2·53	2·48	7
8	2·57	2·54	2·52	2·49	2·45	2·41	2·59	2·56	2·52	2·47	2·42	8
9	2·52	2·49	2·47	2·44	2·40	2·36	2·54	2·50	2·46	2·42	2·38	9
10	2·47	2·45	2·42	2·39	2·36	2·32	2·49	2·46	2·42	2·38	2·34	10
11	2·43	2·41	2·38	2·35	2·32	2·29	2·45	2·42	2·38	2·34	2·30	11
12	2·39	2·37	2·35	2·32	2·29	2·25	2·41	2·38	2·35	2·31	2·27	12
13	2·36	2·34	2·32	2·29	2·26	2·23	2·38	2·35	2·32	2·28	2·24	13
14	2·33	2·31	2·29	2·26	2·23	2·20	2·35	2·32	2·29	2·25	2·21	14
15	2·31	2·29	2·26	2·24	2·21	2·18	2·32	2·30	2·26	2·23	2·19	15
16	2·28	2·26	2·24	2·21	2·19	2·15	2·30	2·27	2·24	2·21	2·17	16
18	2·24	2·22	2·20	2·17	1·15	2·11	2·26	2·23	2·20	2·16	2·13	18
20	2·20	2·18	2·16	2·14	2·11	2·08	2·22	2·19	2·16	2·13	2·09	20

TABLE 7—*continued*

Capacity Susceptance of Cable, 25 Cycles—continued

For three-phase irregular spacing use $D = \sqrt[3]{abc}$

For three-phase regular flat spacing use $D = 1{\cdot}26d$

For a two-phase line the spacing is the average distance between centres of conductors of the same phase

Sizes for both Copper and Aluminium Cables

B.W.G.	No. 000	No. 00	No. 0	No. 1	No. 2	No. 3	No. 4	
Copper Wire	211,600	167,800	133,100	105,500	83,690	66,370	52,630	Circular
Number of Wires assumed	7	7	7	7	7	7	7	
Diameter (cm.) Inches	0·426	0·378	0·4117	0·3383	0·2985	0·2621	0·2301	0·2117	
Spacing in Feet	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	$\times 10^{-2}$	
1	3·05	3·50	3·46	3·30	3·27	3·19	3·10	3·03	1
1·5	3·32	3·23	3·14	3·06	2·90	2·92	2·85	2·78	1·5
2	3·10	3·03	2·95	2·88	2·82	2·75	2·69	2·63	2
2·5	2·96	2·80	2·82	2·76	2·70	2·64	2·58	2·53	2·5
3	2·85	2·79	2·72	2·66	2·61	2·55	2·50	2·45	3
3·5	2·76	2·70	2·64	2·59	2·53	2·48	2·43	2·38	3·5
4	2·68	2·63	2·58	2·52	2·47	2·42	2·38	2·33	4
4·5	2·63	2·58	2·52	2·47	2·42	2·38	2·33	2·29	4·5
5	2·58	2·53	2·48	2·43	2·38	2·33	2·29	2·25	5
6	2·50	2·45	2·40	2·35	2·31	2·26	2·22	2·18	6
7	2·43	2·38	2·34	2·29	2·25	2·21	2·17	2·13	7
8	2·38	2·33	2·29	2·25	2·20	2·16	2·13	2·09	8
9	2·33	2·29	2·24	2·20	2·16	2·13	2·09	2·05	9
10	2·29	2·25	2·21	2·17	2·13	2·09	2·06	2·02	10
11	2·25	2·21	2·17	2·14	2·10	2·06	2·03	2·00	11
12	2·22	2·18	2·14	2·11	2·07	2·04	2·00	1·97	12
13	2·20	2·16	2·12	2·08	2·05	2·01	1·98	1·95	13
14	2·17	2·13	2·10	2·06	2·03	1·99	1·96	1·93	14
15	2·15	2·11	2·07	2·04	2·01	1·97	1·94	1·91	15
16	2·13	2·09	2·05	2·02	1·99	1·96	1·92	1·89	16
18	2·09	2·05	2·02	1·99	1·96	1·92	1·89	1·86	18
20	2·06	2·02	1·99	1·96	1·93	1·90	1·87	1·84	20

APPENDIX.

Z	$= 30{\cdot}691$	$+i$	$100{\cdot}14$
$\frac{Y}{2}$	$= 0{\cdot}00001562$	$+i$	$0{\cdot}0000383$
	$+0{\cdot}000479$	$+i$	$0{\cdot}001564$
	$-0{\cdot}003835$	$+i$	$0{\cdot}001175$
$\frac{YZ}{2}$	$=-0{\cdot}003356$	$+i$	$0{\cdot}002739$
$\frac{YZ}{4}$	$=-0{\cdot}001678$	$+i$	$0{\cdot}001369$
$\frac{YZ}{6}$	$=-0{\cdot}001118$	$+i$	$0{\cdot}000913$

Multiply these together to give $\frac{Y^2Z^2}{6\times4}=\frac{Y^2Z^2}{2\cdot3\cdot4}$

	$+0{\cdot}0000018$	$-i$	$0{\cdot}0000015$
	$-0{\cdot}0000012$	$-i$	$0{\cdot}0000015$
$\frac{Y^2Z^2}{2\cdot3\cdot4}$	$=+0{\cdot}0000006$	$-i$	$0{\cdot}000003$
$\frac{Y^2Z^2}{2\cdot3\cdot4\cdot5}$	$=+0{\cdot}0000001$	$-i$	$0{\cdot}0000006$

From (3)

$$E_s=E\left(1+\frac{YZ}{2}+\frac{Y^2Z^2}{2\cdot3\cdot4}\ \ldots\right)+IZ\left(1+\frac{YZ}{2\cdot3}+\frac{Y^2Z^2}{2\cdot3\cdot4\cdot5}\ \ldots\right)$$

$E=100{,}000$

$\frac{YZ}{2}+\frac{Y^2Z^2}{2\cdot3\cdot4}=-$	$0{\cdot}0033554$	$+i$	$0{\cdot}002736$

Therefore

$E\left(\frac{YZ}{2}+\frac{Y^2Z^2}{2\cdot3\cdot4}\ \ldots\right)=-335{\cdot}54$		$+i$	$273{\cdot}6$
$I=$	$250{\cdot}0$	$-i$	$187{\cdot}5$
$Z=$	$30{\cdot}691$	$+i$	$100{\cdot}14$
	$7672{\cdot}750$	$-i$	$5754{\cdot}5625$
	$18776{\cdot}250$	$+i$	$25035{\cdot}0$
$\therefore IZ=$	$26449{\cdot}000$	$+i$	$19280{\cdot}4375$
$\left(\frac{YZ}{2{\cdot}3}+\frac{Y^2Z^2}{2\cdot3\cdot4\cdot5}+\ \ldots\right)=-$	$0{\cdot}0011179$	$+i$	$0{\cdot}0009124$
	$-29{\cdot}56733$	$+i$	$24{\cdot}17206$
	$-17{\cdot}59147$	$-i$	$21{\cdot}55360$
$\therefore IZ\left(\frac{YZ}{2{\cdot}3}+\ \ldots\right)=-47{\cdot}15880$		$+i$	$2{\cdot}61846$

Summarizing we get :—

$E=100{,}000$

$E\left(\frac{YZ}{2}+\ \ldots\right)=-335{\cdot}54$		$+i$	$273{\cdot}6$
$IZ=$	$26{,}449$	$+i$	$19280{\cdot}4375$
$IZ\left(\frac{YZ}{2}+\ \ldots\right)-47{\cdot}15880$		$+i$	$2{\cdot}61846$
	A		B

Add these together to get E_s

$\therefore E_s=126{,}066{\cdot}301+i\ 19{,}556{\cdot}65$

$\therefore E_s=127{,}574$

At no load $I=0$, therefore E_{so} will be the sum of the first two lines of the above summary.

	A_o		B_o
$\therefore E_{so}=99{,}664{\cdot}46$		$+i$	$273{\cdot}6$

$\therefore E_{so}=99{,}665$

I_s and I_{so} are similarly derived from equation (4).

THE EFFECT OF AIR AND WATER ON MATERIALS USED IN ENGINEERING WORK.

By H. E. YERBURY, Member.

Paper received 16 *December*, 1918, *and read before the* NORTH MIDLAND CENTRE, 11 *March*, 1919.)

SYNOPSIS.

Constitution of air—dry and below dew point.
Theories of corrosion—chemical and electrolytic.
Effects on iron and steel and non-ferrous alloys.
Specific instances of damage to metals, etc., subjected to air and water.
Preservation of cast and wrought iron and steel under various working conditions.
Summary of conclusions.

The effect of air and water—whether pure or impure—on engineering materials and structures is a subject deserving serious thought and attention, as its influence is well known to every engineer engaged on construction and, more especially, on maintenance work.

In the majority of cases it is detrimental to the useful life of such material.

The elementary facts covering the constitution of what might be called ordinary atmospheric air and water must first be defined, and subsequently their observed effects noted on different metals under various working conditions.

The ordinary atmosphere contains one part by volume of oxygen to four parts of nitrogen. Owing to the greater solubility of oxygen, however, air dissolved in water contains one part of oxygen to less than two parts of nitrogen. These two gases have different rates of diffusion and may be partially separated by their own molecular movements. Air also contains hydrogen and variable quantities of the following gases: aqueous vapour, carbon dioxide, ammonia, nitric acid, ozone, and argon, all mingled together and not combined; it also includes suspended matter, both liquid and solid, and partly organic and partly mineral, including sodium chloride and sulphates. The quantity of moisture or aqueous vapour in the atmosphere can readily be measured by a hygrometer. If a mass of air be cooled gradually its temperature will be lowered to a point at which the air will be saturated by the quantity of vapour then mixed with it. This temperature is called the dew point, and the air is then in a condition in which its effect on metals is increased, as the liquid forms an electrolyte.

Water may be decomposed by the very smallest quantities of electrical energy. A current of electricity passing through water splits it up into its constituent elements, hydrogen and oxygen, and is dependent on ions for its transit. A current exerts a certain force on water, whether in the ionic state or not. This action is known as electrical endosmose. Hydrogen is the lightest of gases, and is the great reducing agent. It is sluggish at ordinary temperatures but very active at high temperatures, and reduces most metals because it combines with the oxygen of metallic compounds, that is, it removes oxygen by combining with it. Hydrogen carries the positive charge and oxygen the negative charge; or, in other words, hydrogen is electro-positive to oxygen.

THEORIES OF CORROSION—CHEMICAL AND ELECTROLYTIC.

Rust, corrosion, and oxidation may be said to be synonymous when applied to metals.

The two principal theories of corrosion are the acid and the electrolytic. The former is based on three factors which play an important and necessary part, and may be briefly described as (1) an acid, (2) water, (3) oxygen. The process of rusting or corrosion of iron and steel is always started by an acid, and even the weakest acid suffices. The acid changes the metal to a ferrous salt and hydrogen is evolved. Water now acts upon the ferrous salt with the assistance of oxygen, and causes the ferrite in this salt to separate out as ferric hydroxide, thus liberating the same amount of acid as was used in forming the ferrous salt. A cyclical process is established, and the acid set free again acts on the metal, forming more ferrous salt which is again decomposed.

When the acid solution is entirely neutralized by, say, an alkali, the process is arrested.

The author favours the electrolytic theory of corrosion, which is now almost universally accepted, and is the most convincing, since its effects can be demonstrated. The process is in full accord with modern thought based on the fact that all metals possess a solution pressure which may be termed their escaping tendency to pass into the dissolved state. The solution pressure varies with the solvent, may be positive or negative, and is calculable for every solution. Even in pure water, or under conditions where a film of water may condense upon it, metals have a tendency to pass into solution. Pure water is seldom encountered in ordinary engineering work, as water usually contains traces of salts—acids or bases—with consequently a still greater tendency for the metals to pass from the atomic condition into the ionic condition. Ionization is the process by which ions (particles charged with electricity) are produced, in solid, liquid, or gases. The migration velocity of ions is dependent chiefly upon the number of ions in solution. When water is an electrolyte a small proportion of its molecules are ionized, yielding equivalent amounts of hydrogen and hydroxyl ions which take part in the conductance

with whatever other ions there may be present. (H=ions of the acid; hydroxyl=ions of the base; $H+OH=H_2O$.) Hydrogen bears a single positive charge and the hydroxyl group an equal and opposite negative charge. Hydrogen and metals are capable of forming or producing only positive ions, but both positive and negative must be simultaneously produced before electrical energy comes into existence. The conductance of an electrolyte nearly always increases with increasing temperature. As hydrogen figures largely in the process of rusting and general corrosion its characteristics should be noted. Atomic weights as calculated in ordinary chemistry represent the weight of a molecule in terms of hydrogen, which is taken as unity. The molecule of hydrogen is computed to be built up of 18 electrons, and other elements have a greater number in proportion approximately to their atomic weights.

The discovery of radium enabled scientists to arrive at the conclusion that the chemical elements are composed of minor atoms which are described by the term "electrons." That discovery has revolutionized thought in many departments of chemistry. The electron is considered to be a unit of electricity or a minute particle carrying a negative charge, or it may be an atom of ether carrying a definite charge of electricity.

In the presence of a gas, electrons become ions. An electric current conducts electrolytically by the migration of ions. All those elements which produce negative ions act exclusively as oxidizing agents. As metals can only produce positive ions, followed by the formation of negative ions (or the disappearance of positive ions by mutual attraction), the metals themselves are thereby oxidized.

In studying the mechanism of corrosion, the effect of osmotic pressure (or the pressure derived from the dissolved particles) must be considered. Osmotic pressure, just as gaseous pressure, increases with a rise in temperature, and diminishes with a fall of temperature. This osmotic pressure opposes the electrolytic solution pressure and consequently tends to drive ions out of the solution. These two forces may be determined from a hydro-dynamic formula, or can be thermo-dynamically equated.

The Nernst formula is the recognized expression for the electromotive force set up and is as follows:—

$$E=\frac{R\,T}{n\,F}\log_e\frac{P}{p}$$

where R=gas constant;
T=absolute temperature;
n=valency of the ion passing into the solution;
F=quantity of electricity in coulombs;
P=solution pressure;
and p=concentration or osmotic pressure of the solution.

When a substance of solution tension P is converted into ions of osmotic pressure P, no work is done and there is equilibrium. By transferring the ions from osmotic pressure P to osmotic pressure p, work is accomplished in the same way as can be calculated from a gas in passing from a pressure P to a gas pressure p.

If equilibrium could be established there would be no corrosion; but the other ions, hydrogen and hydroxyl, and their effects must be considered before passivity takes place. Passivity is due to an exceedingly small ionization velocity of the metal. It is of frequent occurrence with iron and steel and other metals in alkali solutions.

As oxidation signifies interaction with oxygen, the function of oxygen in the process of rusting and corrosion is to oxidize the layer of hydrogen on the surface of the metal, and also to precipitate the iron and so remove ferrous ions from the solution. A film of hydrogen gas offers a high resistance, the action being termed polarization, and were it not removed it would arrest the further solution of the metal, and as the mass of metal and the solution are of opposite polarity the solvent action would cease were it not for other factors. The destruction of the hydrogen film in ordinary corrosion is accomplished by the oxygen of the atmosphere which is dissolved in the water or electrolyte, or it may be removed by water in motion.

It follows that any substance which dissolves or reacts with hydrogen accelerates corrosion. This is found in practice to be universally true.

Effects on Steel and Iron and Non-ferrous Alloys.

The happy time has not arrived when steel can be made from pure iron with only the other desired elements added. At the moment it is largely a matter of abstracting in the process of manufacture the undesirable constituents which are unfortunately ever present in commercial steels used in general engineering.

It is well known that the useful life of a metal varies greatly with the composition of the metal. A study should therefore be made of the conditions under which steel and iron have to be employed, before determining the best and most suitable composition. By its lack of homogeneity in composition and structure the average steel surface in water as it occurs in nature presents all the conditions necessary for active electrochemical corrosion. Iron and steel may be regarded as complex mixtures, and the three factors affecting their useful life under the influence of air and water are: chemical composition, homogeneity, and physical conditions.

Wrought iron generally is more resistant to corrosion than steel. It contains from 0·06 to 0·15 per cent of carbon. Steel containing pearlite is very readily attacked under the potential differences set up by that structural constituent. It provides cathodes to the anodes of the ferrite in solid solution. Non-homogeneity of a metal favours pitting and general corrosion, as it provides a large number of small anodes and cathodes, and therefore greater action than would be the case with one large electrode. It has been proved that corrosion of steel in either acidulated or salt water was greatest when it contained the maximum percentage of carbon.*

Pure carbon steels contain larger grains than alloy

* L. Aitchison, *Transactions of the Faraday Society*, 1915–16, vol. 11.

steels and as the ferrite (pure iron) is always attacked, it is assumed that the carbides composed of carbon with a metal act as negative electrodes or cathodes to the positive anode elements. Iron and steel have the power of occluding a considerable amount of gas—either hydrogen, nitrogen, or carbonic oxide. Oxygen is known to exist in steels, especially in very low carbon steels, where it combines with either iron or carbon and gives either carbonic oxide or ferrous oxide, the latter being dissoluble in iron, and consequently being very thin slag. Its presence greatly assists in intensifying the rate of corrosion in any electrolyte.

In addition to the chemical composition of steel affecting its rate of corrosion, thermal and mechanical treatment are factors which cannot be ignored. Although a particular class of steel such as chromium is almost immune from corrosion, ordinary commercial steels in structural work are subjected to stresses where bent and riveted, and anodic and cathodic conditions are set up. A properly annealed metal in contact with a cold-worked metal invites active galvanic action in the presence of moisture, as the cold-worked metal contains a certain amount of latent positive energy ready to re-appear as electrical energy in any electrolyte. Segregated impurities—particularly sulphur in steel—play a mischievous part, especially in thin steel pipes. Although no abnormal impurities may exist, conditions are set up in the process of riveting steel pipes which produce a greater tendency to corrosion than with the usual chilled surfaces of cast-iron pipes.

Grey forge pig iron is generally used for castings, and this contains a large amount of free graphitic carbon (about 2·9 per cent.), also silicon (about 2·3 per cent.), and is much more susceptible to corrosion and pitting than what is known as white iron, which contains up to about 0·9 per cent. of graphitic carbon and 0·4 per cent. of silicon, and is low in phosphorus. The comparatively large quantity of graphite in grey iron produces a good electrode to act in opposition to the ferrite which is near it; whereas in white iron nearly the whole of the carbon is in the combined state.

It is unfortunate that there are foundry difficulties when white iron is used. It is also more crystalline and brittle and difficult to machine.

In the author's opinion the time is fast approaching when engineers will specify the constituents of castings, including pipes, when they are to be used in special positions and under conditions where salt or acidulated water or other good electrolyte is present.

The natural resistance to corrosion by cast-iron pipes as compared with wrought-iron or steel pipes is due to the skin, or chill, on the external and internal surfaces which brings about a partial change to white iron.

Where pipes are buried, the nature of the soil should be examined, and their useful life may be extended many years if care is exercised. For instance, it is well known that where pipes are buried near or on ashes, and water is present, active corrosion and pitting is readily set up. Microscopical examination and analyses show clearly that this class of pitting is identical with the damage which takes place if a current of electricity enters a pipe and is allowed to flow to earth. Clayey character of soil leads to an increased retention of the electrolyte, and it is therefore advisable to lay pipes in a layer of sand or porous earth.

Many cases can be cited of lead pipes and sheeting being destroyed where condensation of moisture has taken place, and commercial white lead and the higher oxides of red lead have been formed beneath the corroded parts.

Lead pipes should be enclosed in wooden casing and not exposed to the solvent action of lime, plaster, mortar, or cement, as a free alkali, especially when assisted by moisture, invariably attacks lead. This action is far greater with lead when embedded in concrete than with any other metal. Lead is electro-positive to copper and brass, and electro-negative to iron and steel.

Some interesting cases of corrosion of cast-iron pipes and also lead sheathing of dry-core cable have been brought to the author's notice. In a recent instance a large portion of the lead had been destroyed, and pitting and general corrosion of the interior and exterior of the cast-iron pipe had also taken place. As this particular cable had been damaged in a similar manner near the same place some few years ago, an analysis of the soil surrounding this pipe has recently been made. It contained 21·18 per cent. of water and the ash content was about 77 per cent., and the sample showed the presence of a strong ammonia compound in the following amount, 0·0252 per cent. as ammonia, or 0·0672 per cent. as ammonium carbonate. On heating there was an objectionable smell of urea, and undoubtedly urine has been percolating the soil at this place. When urine is exposed to the air fermentation sets in, and the urea is converted into ammonium carbonate. Some water had entered the interior of the pipe, and electrolytic action had taken place between the cast iron and lead, and the exterior of the cast-iron pipe had been attacked and Fe_3O_4 and also Fe_2O_3 had been formed. A careful test of the differences of potential gave the following readings:

Lead to iron pipe	6 to 15 millivolts
Between the two ends of the lead sheathing when separated,	100/400 millivolts.
Between the two ends of the cast-iron pipe when separated,	60/100 millivolts with varying plus and minus signs.
Between two sound pipes, a steady reading of	200/250 millivolts.

It will be seen that although a slight leakage current is indicated, the voltage is no higher than would be expected where self-corrosion is taking place. These pipes and cables had been in service 19 years. The white powder from the decomposition of the sheathing was carbonate of lead, resulting from slow oxidation and exposure to the CO_2 in the air and the liquid from the soil.

Lead being electro-negative to iron, it was found that a quantity of iron oxide had been deposited on the

lead sheathing, and the oxides in the soil contained iron, lime, and magnesium. The general condition of the cast iron and lead was characteristic of slow electrolytic action, which could undoubtedly be produced by local action or self-corrosion in this strong electrolyte without any leakage current.

Another fault occurred on a 204-pair cable where the iron pipe was decomposed and perforated, the lead sheathing being badly pitted and parts eaten away, and the wet paper and copper wires exposed. This action was caused by a leaky steam pipe which crossed the telephone pipe at right angles, making the ground wet and hot, thus producing an electrolyte and vigorous electro-chemical activity.

Self-corrosion of iron pipes proceeds rapidly in certain acid soils, and if there is an abundant supply of oxygen in the soil water the tendency will be to form ferric oxide and ferrous or black magnetic oxide where there is a small supply of oxygen. The author believes it is impossible to tell with absolute certainty from the examination of a corroded metal whether or not the corrosion has been caused by stray leakage currents, although it must be admitted that corrosion in any electrolyte is accelerated where a stray current exists. The theory is submitted that moderate heat alone without moisture will not disturb the equilibrium of metals and cause intra-molecular and intra-atomic energy to be liberated with the production of an electromotive force. A case in point occurred in Sheffield where a 102-pair cable passed close to some steel furnaces, the outer wall of which bordered on the footpath. A fault developed on this cable, and it was found that the furnace heat had charred the paper to a carbonized state without in any way injuring the sheathing or pipe.

Bronze, copper, and brass, in common with other metals, pass into solution dependent on the electrolyte.

It has been noted by many observers that corrosion of steel is not accelerated by contact with other metals or alloys. For instance, steel rods or shafts sleeved with bronze do not set up serious electrolytic action even in salt water, and bronze and brass nuts can be easily screwed off steel bolts, whereas under similar corrosive conditions a steel nut could not be moved.

Boilers.—Much damage has been occasioned by internal and external pitting and corrosion of all types of boilers. Iron and steel subjected to tension or uneven strain possess a greater solution pressure than ordinary iron and steel. The tendency, therefore, is for these to corrode more easily, and electrical energy always passes in such a direction that the stressed or unstable may pass into the stable form. Annealing and normalizing are therefore always desirable, whenever possible, on metal which has been stressed. As may be expected, corrosion is often started at the rivets and joints. The breathing action on parts of boiler drums sets up alternating stresses, and parallel grooves of corrosion in boiler plates have been traced to this cause.

New steel plates are usually covered with a thin film of magnetic oxide, and when a plate is stressed in the bending process this film cracks, thereby exposing the underlying metal. In the presence of water or water vapour electrolytic action is often started along these lines, as this mill scale is electro-negative to iron; hence free metal dissolves at the anode. Sheets containing an excess of phosphorus, or if rolled from an ingot in which piping or segregation has taken place, have inherent defects which invariably manifest themselves when subjected to air and water.

Internal pitting and corrosion in boilers and pipes, etc., are largely due to the presence of air in the feed water. The amount of air present will of course depend on the source of supply, and may be from 1·5 to 5 per cent of the volume of the water, the chief gases dissolved being carbon dioxide, oxygen, and nitrogen. Carbon dioxide and oxygen expelled by boiling often set up a corrosive action in the tops of steam drums and near the water-line.

In the author's opinion the time is rapidly approaching when measures will be taken to eliminate as far as possible all air from boiler feed water. It should be very thoroughly removed from condensers, preferably by dry air pumps, and the heat units from all auxiliary sources should be utilized so as to obtain the highest possible temperature of the feed water. Air dissolved in water can best be liberated by breaking the water up into as fine a spray as possible at a high temperature in a vacuum tank before pumping into the boilers. The most effective way of minimizing the quantity of air in feed water appears to be in a closed system, whereby the de-aerated condensate and make-up water is pumped direct to the boiler feed-range. In this system the make-up water in a surge tank would of course be a component part of the closed system, and if the water were required to be measured this would be done by a Venturi tube.

Exterior corrosion of boiler plates and tubes is generally brought about by the sulphur in the coal forming sulphur dioxide, which with the steam generated from the moisture in the coal, together with the water formed by the burning of hydrogen, produces an acidulated electrolyte. This, however, is inactive unless the temperature of the boiler is sufficiently low for moisture to be deposited. It may therefore be said that the action of pitting and corrosion is greater in a boiler which is warm than when the boiler is steaming at full capacity. Careful and systematic tests should be regularly made to ascertain if there are any leaky condensers, as many boiler troubles have been traced to that source. The simplest test is the electrical conductivity one, as the conductivity is proportional to the percentage amount of the substance dissolved in the water. Owing to the conductivity increasing with a rise in temperature, corrections for temperature should be made.

Tanks, etc.—Hot water feed-tanks—especially where exhaust steam is discharged and air liberated—are very susceptible to corrosion, and hard, close-grain cast iron is recommended for tanks in preference to steel plates. Steel stays are often attacked, and stays and bolts made of Low Moor iron are generally free from corrosion. The quality of bolts and nuts used in places and under conditions where corrosion may be expected is a matter of primary importance, since many instances may be cited where steam-pipe joints

have given way, and it has been found that the bolts have been severely corroded, the electrolyte being condensed steam from leaky jointing material. Rustless steel is recommended for steam relay and double-beat valve spindles as freedom of motion is often retarded by the film of oxide which soon covers spindles made of ordinary steel.

Where expansion joints or bellows pieces for water pipes have been made of iron or steel riveted together and galvanized, a very short life has resulted. Galvanizing so called is really dipping, and there is no galvanic action or deposition. Zinc often contains antimony, arsenic, and iron, and although iron is preserved so long as the zinc is intact, whenever the zinc is dissolved or broken by expansion, or worn by the friction of water, it becomes more electro-negative in character and corrosion is accelerated, especially on the strained portions around the rivets. Copper is recommended for expansion pieces, as its solution pressure is comparatively low.

Rotary pumps.—Much trouble and expense has been occasioned by the failure of rotary pumps, and in the author's experience impellers have had to be renewed after about 12 months' working.

The principal trouble has been caused by pitting, corrosion, and cavitation, with the result that the efficiency has been impaired and impellers and shafts have often been ruined in from one to two years when working with river water and also when dealing with condensate containing air from surface condensers, more especially where pumps are running at a high speed.

Much trouble can undoubtedly be attributed to bad design. Special attention should be given to the design of the casing and the impeller of a rotary pump, also the discharge passages or ports from the pump to the pipe line. Castings should be constructed of a volute form, and there should be no break in the change from velocity to pressure. Cavitation is often brought about by a bad design of volute, forming pockets for the retention of water vapour and gases liberated from the water under a vacuum.

In addition to pitting and corrosion (especially on cast-iron impellers) due to air in the entry and discharge ports and guide passages, cavitation may be produced by a purely mechanical action caused by the kinetic energy of the molecules of water. In this case the crystals themselves would be broken up, whereas ordinary corrosion invariably takes place along crystal boundaries. If the design of pump does not permit the breaking up of the water, and all ports and passages are closely swept, corrosion and pitting are minimized if not entirely prevented. High-tensile steel shafts should be covered in a brass or bronze watertight sleeve to prevent corrosion in ordinary river circulating-water, as high-tensile steel tends to corrode more quickly than mild steel.

Shafts made from steel containing 14 to 15 per cent. of chromium are almost entirely free from corrosion in circulated salt water, and as a tensile test of from 45 to 50 tons can be obtained with good elongation, the use of stainless steel shafts should be increased in the near future.

The hub or boss of cast-iron pump impellers is often attacked by general corrosion and pitting, and in the author's experience this destructive action has been so great during 12 to 18 months that hubs have been eaten into and the shaft attacked to such an extent that it has been almost impossible to drive off the impeller due to the volume of rust.

The action on other pump parts has been such that nearly all the ferrite has passed into solution, and the remaining so-called iron could easily be cut with a knife.

Impurities in cast metal are greatest where the last portion cools, and there the percentage of phosphorus is invariably high. This facilitates the separation of graphite, opens the grain, and provides many anodes and cathodes for local action to be set up. For the minimizing of corrosion, cast iron should be low in silicon and phosphorus and high in combined carbon, which closes the grain and hardens the iron.

Suction pipes should contain no air pockets, and the pump-suction lift should be as little as possible to obviate air leakage. In this connection drowned pumps are often preferred, although inspection is naturally more difficult.

Special attention should also be given to the design and maintenance of glands, as, from the design of some pumps, air naturally enters whenever the glands are not tight, or through imperfect water-sealing. The capacity of pumps is thereby reduced and there is also a greater tendency to corrosion. It has also been found that circulating water when broken up in cooling towers has absorbed sulphur dioxide, chlorine, and ammonia from the atmosphere, and other soluble and insoluble substances in rain water, all tending to intensify the rate of corrosion, which is accelerated when the water is very hot.

The inlet river water should be admitted where it thoroughly mixes with the cooling-tower discharge water, so as to neutralize any concentrated acidity or impurity which might be brought about by the continual circulation of cooling-tower water only.

High-tensile bronze is recommended for impellers and pump shafts where the water is of a particularly corrosive nature.

Condenser tubes.—Considerable trouble has been occasioned on land and sea by corrosion and pitting of condenser tubes. Apart from the usual pitting which often takes place from the inside of tubes by the action of water, etc., the author has recently investigated somewhat unusual cases of corrosion and pitting which have only taken place on that part of the tube over which the packing or grummet is fitted and retained by the ferrule.

This particular form of corrosion is started and continued from the outside surface of the tube until it is perforated, whereas in the majority of cases all pitting has started from the inside, and is fairly general over the entire surface exposed to the circulating water. It was noted that external corrosion and pitting occurred only on the in-flow ends of the condensers, that is, where the water is first broken up on entering the tubes, and also where the direction is reversed at the other in-flow end of the condensers.

On taking an analysis of the cotton-tape packing after nine years' service it was found to contain :—

Carbonaceous matter	86·85	per cent
Ferric oxide	11·2	,,
Zinc oxide	1·13	,,
Copper oxide ..	0·82	,,

The tubes were of standard brass of the usual 70 : 30 mixture, the actual analysis being :—

Copper	69·75	per cent
Iron	0·17	,,
Lead	0·6	,,
Tin	None	
Zinc (difference) ..	29·28	,,

It will be observed from the analysis of the packing that the water must have been heavily laden with iron oxide, and it appears that some of the circulating water had penetrated down the sides of the screwed ferrules and underneath the packing, the latter acting as a filtering and retaining medium. It will also be seen that zinc and copper had passed into solution.

It is significant that on other condensers working under the same conditions no electrolytic action had taken place, the only difference being in the composition of the tubes, which were of Admiralty tube mixture, viz. 70 : 29 : 1.

The author believes that a more perfect amalgam or alloy is obtained if tin is present, and although tin will dissolve in water the action is much smaller than on zinc, lead, or copper.

Brass tubes tinned inside and outside are protected to a limited extent both mechanically and electrolytically, and have therefore a longer life.

In the case under review it appears that the oxide of iron in the circulating water had been deposited and retained in the absorbent packing.

Precipitated oxide of iron is a good carrier of oxygen, and this gas would probably be absorbed when the water was broken up and air liberated on its entry into the tube ends. Conditions, therefore, were such that wherever the packing allowed oxide of iron, air, and possibly slightly acidulated water to be retained, all elements were present for galvanic action to be set up. Care should therefore be given to the size of the hole in the tube plate and to the fit of the tube and ferrule, so that the packing may be kept as watertight as possible. A somewhat analogous case may be cited on, say, cast-iron pipes, where a speck of rust or nodule has been formed and the electrolytic action would increase and be aided by the increasing bulk of rust which helps to retain the electrolyte, thus creating with the iron a galvanic couple.

If a piece of zinc and a piece of brass are inserted in distilled water 1 inch apart an exceedingly small difference of potential is set up. In drinking water from a tap about 2·5 millivolts would be generated, and in river and other circulating water the voltage would be from 20 millivolts up to 0·88 volt with rise of temperature. It therefore follows that great care and attention should be given to the composition of all metals where these are used in water at a high temperature, as this galvanic action is intensified approximately 100 per cent for every 10 degrees C. rise in temperature, the detrimental effect varying where the electrolyte is stationary or in motion.

A special Corrosion Committee is now investigating the cause of condenser-tube troubles, and the result of their researches will doubtless be made public in due course. Suffice it to say at the moment that the theory favoured is the electrolytic one, as it has been demonstrated that where an extraneous current has been applied such as in the Cumberland process, thereby making all tubes cathodic, the trouble has been minimized if not entirely prevented. A current density of about 0·1 ampere per square foot of surface is recommended for this process.

Turbo-generators.—The effect of moisture on electrical generators due to the application of wet-air filters has often caused trouble. It has been found that, partly owing to the fluctuating load on a generator, the temperature of the machine has varied so that when the machine is lightly loaded the temperature rise has been insufficient to dry the moist air from the filter, with the result that the insulation resistance has been reduced to a dangerous extent.

On the other hand, if the temperature is high, all moisture is quickly evaporated and undesirable salts are deposited on the windings, thus providing a path for leakage on extra-high-tension machines.

It appears that in order safely to withstand saturated air, generators should be impregnated under vacuum with an insulating varnish. By this process, with proper insulating materials, the general insulation resistance should be high enough to withstand satisfactorily the cumulative effect of a wet-air filter.

On extra-high-tension machines it is now deemed advisable to discard metal packing pieces, owing to their oxidizing tendencies and conductivity, and to revert to wood or moulded insulating compounds.

Economizer pipes and boxes.—With water below 100° F., corrosion is often set up on the outside of economizer tubes, whether of cast iron or steel, due to condensation of moisture from the passing gases. This moisture is an exceedingly good electrolyte, as it invariably contains sulphuric acid, derived originally from the sulphur in the coal forming sulphur dioxide during the process of combustion and combining with the vapour present. Unless the feed water is heated, at least one-sixth of the tubes are often corroded to about 18 inches from the bottom boxes, and the boxes also suffer badly. As metals cannot corrode or pass into solution without moisture, the obvious way to prevent external corrosion is to raise the temperature of the water by means of feed heaters or circulators fitted to the economizers, so that hot water is made to circulate from the lowest parts. In other words, to prevent the formation of moisture, or where water is objectionable, measures should be taken to avoid a sudden reduction in the temperature of the air or gases. It may be said that, with water at a temperature of 110° F. and upwards, no trouble need be anticipated, assuming that the boxes and pipes are good castings and no sweating is taking place. Where internal corrosion is found, an analysis of the feed water is required with

suitable chemical treatment. Cast-iron economizers should be made of metal having the lowest possible percentage of free graphitic carbon.

Turbine blades.—Much research work is still being done in order to produce a metal which will withstand the stresses to which turbine blades are subject, and to be entirely immune from corrosion.

In the early days of turbine manufacture steel blades were found to be pitted and corroded badly, especially when a turbine was frequently stopped and started again after a lengthy period. It has also been found that where leakage of steam has taken place at a closed stop-valve, thereby allowing moisture to condense on the blading, electrolytic action is set up, resulting in blade erosion and loss in efficiency. Cases are on record where certain rows of blading have corroded where the steam temperature has dropped below dew point, and only at this stage in the length of a turbine has damage been done.

Corrosion of turbine blades has also been traced to carbon dioxide in the steam derived from unsuitable feed water, the remedy for such action being the elimination of the carbonates from the feed water by chemical treatment. It is unfortunate that some chromium rustless steels have physical properties unsuitable for turbine-blade stresses; non-ferrous alloys are therefore frequently used. It should be noted that no corrosion can take place with any metal in a dry state, so that by the entire elimination of moisture the primary medium for corrosive action is non-existent. It has been found that water will dissolve a greater number of metals than any other liquid, and metallurgists are now engaged in research work evolving alloys of the lowest possible solution pressures, and with physical properties suitable for the work such metals have to withstand.

Injury to non-ferrous metals, etc.—The presence of vapour or water deposited on brass and other alloys often causes verdigris, which is the result of the metal passing into solution. These solution pressures vary greatly with the composition and state of the metal. Where it has been strained, say, in the process of bending, the corrosive effect is intensified.

Sharp right angles should always be avoided and easy bends substituted. Much damage has been done to extra-high-tension electrical machines and apparatus where silent static discharges or sparking has taken place, nitrous oxide and ozone being formed, and in the presence of moisture corrosion has started, with serious results. Ozone is a very great oxidizing agent and most metals are quickly attacked by it.

If an electrical discharge cannot be prevented, care should be exercised to see that moisture and condensation do not settle on these parts.

In the author's experience much trouble has resulted from vapour condensing on cold porcelain insulators causing brass contacts, causing serious oxidation, high resistance, and eventually open circuits. It is now generally admitted that all extra-high-tension switchgear and auxiliary switch and fuse contacts should be enclosed if possible in oil.

The quality of the oil is of supreme importance, and it should be free from every trace of water and acid.

Many animal and vegetable oils and compounded oils are corrosive, and many instances are on record of journals and brasses being badly pitted, due to the presence of acid in the lubricating oil. Acids are also formed by saponifiable oils which exert a corrosive action on brasses, producing de-zincification. Mineral oils are not saponified by steam and, if pure, have no corrosive action.

Zinc having high electro-positive characteristics, and lead also being electro-positive to copper and brass, the author thinks that as alloys of copper and tin only—in the proportion of 91 per cent of copper and 9 per cent of tin—are now made (Morrison bronze), and tests up to about 45·7 tons per square inch can be obtained with 22 per cent elongation on rolled rods, zinc will be looked upon with suspicion and disfavour in many cases. Tests on the corrodibility of standard gunmetal compared with the above mixture show that in a saturated salt solution Admiralty gunmetal will pass into solution more readily than an alloy containing no zinc, and as it appears that zinc is an unstable metal better results can often be obtained with mixtures containing no spelter.

The destruction of galvanized iron is brought about by the zinc being dissolved by moisture. This action is more easily accomplished on commercial zinc than on pure zinc. In a dry state, zinc, being electro-positive to iron, preserves the iron in a perfect condition through its impermeability, and only when an electrolyte such as rain water is present is electrolysis set up, the zinc destroyed, and the underlying metal attacked.

Protection of outside structures.—In the author's opinion sufficient study has not been given by engineers in the past to preservatives and protective coatings for iron and steel. It is a platitude to say that, where service conditions are abnormal, more care is required in specifying the quality of paint than would be necessary for normal conditions. Speaking generally, paint should be totally inhibitive as well as protective, and should possess thorough insulating and moist-proof properties.

The coating should have the same coefficient of expansion as the metal, so that it will not be affected by changes of temperature. It should also possess acid-resisting as well as alkali-resisting qualities.

Certain inaccessible parts of steel structures under special conditions should be painted with an elastic medium which at all times retains its elasticity.

It is considered preferable to have a chemical combination and affinity of the pigment and vehicle, and not a mechanical mixture only, although graphite is still largely used for coating steelwork, and is fairly satisfactory especially when lead is added to the pigment to give it a better hold on the metal. All graphite paints are mechanically mixed, and graphite being inert has no action upon the oil, a chemical combination being therefore impossible.

Linseed oil is the principal vehicle used in all paints, but different pigments produce different results. Linseed oil absorbs oxygen from the air, and thereby its volume is increased and also its weight, a substance known as linoxyn being formed, which on continued oxidation evolves carbon dioxide and water. This

electrolyte furnishes a medium for electrolysis to be set up between the metal and the pigment, the former being the anode and the latter the cathode. Expansion caused by rust exposes the metal surfaces underneath, and in the presence of water vapour further corrosion takes place.

Special paints are now on the market which have been subjected to a curing process by heat treatment in the absence of air. All volatile substances are thereby eliminated, so that when the coating is applied it oxidizes and does not evaporate, thus producing a film impervious to moisture, and the permeability of linoxyn is thereby reduced. All moisture, resin, sulphur, and any other element that would excite corrosion should be eliminated. Certain paints containing dryers, benzine, or neutral oils, have a tendency when dry to dissociate and break the bond between the pigment and the vehicle, and thereby become pervious to moisture. Good results depend on the proper mixing before immediate application. Red-lead paint chemically combined so as to prevent the red lead from separating and settling to the bottom forms a good material, especially for shop coatings.

The colour of the pigment also affects the results, and dark colours are recommended for the protection of iron or steel.

It is most important that steel and iron surfaces should be thoroughly dry and cleaned from mill scale, rust, grease, and dirt, before applying the first coat of paint, which should consist of finely-ground pigment.

Multiple thin coats of paint are recommended in preference to thick single coats for general protective purposes.

The most onerous conditions for preservative compounds are where the metal is alternately wet and dry. Tar and various bitumastic paints and solutions are found to give good results, have low permeability to oxygen and water vapour, and will withstand fairly high temperatures.

Salt is a powerful factor in liberating oxygen from moisture in contact with metal. Structures exposed to salt water are particularly liable to injury unless the metal is kept perfectly dry, salt being a compound of two elements, sodium and chlorine, the latter having a great tendency to yield ions and force the metal to act in the same manner.

In reinforced concrete the cement should be absolutely waterproof, and the steel will then remain in a passive condition, due largely to the alkaline compounds. If concrete is not waterproof, electrolytic action will be started, with the inevitable result that there will be stresses in the concrete due to the products of corrosion and the bond will be destroyed between the re-inforcing metal and the concrete.

With suitable concrete of $1\frac{1}{2}$ inches in thickness surrounding the reinforcements for ordinary atmospheric conditions, and 2 inches for salt-water conditions, no injury can take place.

Summary of Conclusions.

The electrolytic theory is not put forward as a "crystallized dogma," but rather as a working hypothesis or assumption of some general uniformity, with a view to testing its truth by experiment and experience. Modern thought points to the idea that the dominating energy is motion, generally regarded to be electronic. Metals should be considered to be matter in motion; and the active or passive state, determining their life, is dependent on conditions. Electrical changes lie at the basis of chemical actions, and chemical action cannot take place without the presence of an electrolyte. There is no absolutely perfect non-electrolyte. Water, usually containing air in suspension or solution, has the property of dissolving all metals used in engineering work. The author submits that the conditions under which the respective metals are to be used should be carefully studied, as their useful life depends on many factors. Such general terms as "cast iron" and "mild steel" convey little meaning to some manufacturers and users, and a specification of their compositions should accompany an inquiry, more especially where the working conditions are abnormal. Cast iron and mild steel pipes figure largely in engineering, and as the corrosion of the former varies a great deal with the composition, and the life of the latter depends principally on the protective coating, these factors should not be disregarded. Where pipes are buried and not surrounded by concrete the nature of the soil should be studied, as this is of the utmost importance, certain salts and acids being aids to oxidation, while certain alkalies retard such action. Exterior corrosion and solvent action of water on lead pipes may be due to salts in the soil, or the action of organic acids in the water flowing in the pipes. The elimination of atmospheric air or gases is a problem always present, and the detrimental effect of air on working plant and metals is now generally recognized, dissolved oxygen and carbon dioxide being particularly destructive. The author believes that no up-to-date electrical generating plant will be considered complete unless methods and devices are installed for de-aerating boiler feed water, at the same time making the utmost use of all available heat units. It is believed that the majority of troubles in boilers and hot-water pipes are due to the presence of air, and that if de-aerated condensed and make-up water be used in a closed system, greater boiler output and efficiency and longer useful life, with less maintenance costs, will be attained.

Commercial metals are impure, and the greater the impurity the greater is the tendency for them to dissolve and decompose. For instance, pure electrolytic iron has a remarkable immunity from rust, and pure zinc does not pass quickly into solution like commercial zinc. When one realizes that there are now about 20 elements added in steel making, it is obvious that corrodibility must vary with composition. A vast field for experimental research is therefore open to metallurgists, embracing such matters as the presence and effect of galvanic couples formed by crystalline arrangements of positive and negative constituents, and their respective solution tendencies and pressures, and the all-important effect of heat treatment to minimize or neutralize internal stresses, which are always potential and often active sources of trouble in materials used for engineering work.

Rolled metal is usually of a more stable character

than cast metal, and the skin is more resistant than the interior. It has often been observed that, where a casting has been machined or drilled, the newly-exposed metal has been the first to be attacked, being more porous and the constituents being often differently arranged. A humid atmosphere provides the worst conditions for any metal, especially where it cannot be protected, such as rails in tunnels. In such cases it is the province of the metallurgist to furnish steel which from its composition and heat treatment will have the lowest possible solution pressure. Oxidation of metals is often effected by the humid seepage from the pores of the human and animal system, this being particularly corrosive in nature. In delicate metal work, corrosion has been prevented simply by the work-people wearing gloves, and this safeguard has been considered to be essential in certain work of national importance during the war.

In conclusion, it may be said that all metals used in engineering work, notwithstanding their varied composition, are immune from rust and oxidation if kept perfectly dry, and where those conditions are impossible the characteristics of the electrolyte should be studied, as well as the chemical and physical properties of the metals, with the object of increasing the useful life and maintaining the highest possible efficiency.

APPENDIX.

Slide 1 shows decomposition of cast-iron pipes and lead sheathing of telegraph cables.

Slide 2 shows effect of leakage current of 0·4 ampere for six years on iron tubing at base of tramway pole; also samples of corroded iron and steel tubing with no leakage current.

Slide 3 shows a pitted cast-iron pipe without general corrosion, which was buried in soil largely composed of ashes, and was replaced after two years' service.

Slide 4 shows cast-iron impellers of centrifugal pumps corroded in one to two years by the action of river water.

Slide 5 shows corroded cast-iron impeller running in condensate from condenser.

Slide 6 shows samples of corrosion on lead pipes which had been buried about two years.

Slide 7 shows the effect of the products of corrosion on insulated bolts; and general corrosion of steel bolts.

Slide 8 shows blow-holes in weld, caused by the liberation of gases on cooling.

Slide 9 shows samples of ends of condenser tubes pitted and perforated only where packed at the ferrules.

Discussion before the North Midland Centre, at Leeds, 11 March, 1919.

Mr. R. H. Campion: It is interesting to note that the author has adopted the electrolytic theory of corrosion, and the arguments in support of it appear to be sound. The information about the different classes of metal is most interesting, but my experience of wrought iron for boiler-feed purposes is the exact opposite to the author's. The large number of materials that can be attacked is well brought out in the paper, and I am interested in what happened to the 102-pair cable in a cast-iron pipe. The presence of air in boiler feed-water is one of the most difficult problems at the present time, and considerable trouble is found to occur with the piping conveying the feed water to the boiler. I heard of a case some years ago in a Lancashire electricity works where of two centrifugal pumps side by side, made at the same time by the same makers and, as far as was known, of the same material, one became eaten away and the other left intact. The particulars given of suitable designs to prevent cavitation are very useful, and the suggestion to improve the glands and increase the capacity is very instructive. A great deal of trouble has been caused by corrosion and pitting of condenser tubes, and very few plants eventually escape, unless some preventative methods are taken for dealing with the water. I was under the impression that the Admiralty specification for condenser tubes was not suitable for land work, and I thought one of the most fruitful sources of trouble was the pitting of the tubes. I have used the Harris Anderson protector system for some 7 years with varying success, and have tried three different makers of tubes. The protectors installed in 1913 were inserted in the hand-holes in the inlet covers in the first instance, and were made of aluminium, but were afterwards changed to cast iron. A certain allowance has to be made for wear and tear on the life of the tubes, as the condenser is 10 years old. The author's remarks relating to turbo-generators, wet air filters, and metal packing pieces, are well worth noting; most of us will have experienced corrosion in connection with economizers. I should like to hear more about the properties of rustless turbine blading.

Mr. W. A. Christianson: With regard to the relative corrosion of wrought iron and steel, I have had experience with large centrifugal pumps pumping polluted salt water. On different shafts tried, wrought iron was least subject to corrosion, then nickel steel, and ordinary steel was worst of all. Experience with the clearance rings using wrought iron and mild steel was similar, and it was noteworthy that the corrosion on these increased at the weld. This was overcome by making the rings solid forged. It seems clear that the corrosion of steel is reduced with the carbon content, hence the better results with wrought iron. The author has submitted photographs of centrifugal pump impellers which have suffered corrosion on the vanes at the point of entry. I should be inclined to ascribe this more to erosion than corrosion, assisted by the probably less perfect nature of the metal at this point as the result of casting. With regard to condensers, I have had some most unfortunate experience with corrosion caused by the circulating water being acid-polluted by chemical works. Those parts of the condenser nearest to the circulating water outlet, where the temperature was highest, suffered most and failed first. On one of the condensers, which was three-pass, the

last-pass tubes were finally reduced to less than half their original weight before final failure. The corrosion in question was fairly uniform and did not take the form of pitting. The condenser had ultimately to be entirely renewed with tubes and ferrules. The composition of the tubes which failed was the ordinary 70/30 mixture, and they were replaced with 70/29/1 (Admiralty) mixture stated to be less subject to corrosion. The conditions having changed in the meantime it has not been possible to make a comparison. The corrosion of the ferrules on different condensers, stated to be all of 70/30 mixture, was not the same. In one of them de-zincification took place, rendering the ferrules quite brittle, while on a condenser of another make, the ferrules suffered wastage but no appreciable de-zincification and were not brittle. The electrolytic protection of condensers, which appears perfect from theoretical considerations, probably does not give absolute protection in practice, due to practical difficulties. It appears that the system very much reduces corrosion or pitting, but does not entirely eliminate it. This is what one might expect since the most of the protective current must flow direct to the tube plates and tube ends, leaving the major portion of the tubes comparatively unprotected. The probable variation in the contact resistance between tubes and tube plates must also influence the chances of corrosion in adopting this system, and if the corrosion takes place in proportion to the temperature of the circulating water, it would be advisable relatively to increase the amount of protection in the portions of the condenser subject to the higher temperatures. I am in agreement with the author as to the necessity of thoroughly de-aerating the feed water, and I generally agree with him as to the arrangements necessary to this end. It is worthy of note that the principal condensing-plant makers are alive to this subject and are designing accordingly. Absolute de-aeration is a difficult matter and, in addition to what is done in the initial stages of the plant, it might be advisable to insert air traps at other points in the feed system before the water enters the boilers, say at the outlets of the feed heaters and economizers, if fitted. In spite of precautions, however, it is possible that there is always a certain amount of dissolved air left, which may cause trouble in the boilers, especially with very soft water containing no scale-forming matter. What is the author's opinion as to whether a pure water (as pure as one can get it in engineering practice, though not of course chemically pure) is non-corrosive in boilers, and what treatment, if any, of the same does he recommend? In my opinion it is not, and I consider some treatment is required to make it quite non-corrosive, this being attained by adding an alkaline solution of tannin to absorb oxygen and give the water a definite "permanent" alkalinity, or by adding tannin solution only if the water is already sufficiently alkaline by the presence of sodium salts. I have been informed that in boilers 25° alkalinity to methyl orange is necessary to prevent corrosion. The alkalinity of the feed water to attain this might only be of the order of about 1°, the higher figure being reached in the boilers through concentration. This question assumes more importance with the use of the purest or softest possible water as is now becoming customary. The subject of boiler corrosion, its causes and prevention, is still somewhat obscure, and more enlightenment is required, as well as regular scientific attention by users. Economizers tend to act as a protection to boilers, first by reducing the strength of any corrosive elements present in the feed, and secondly by giving a hotter feed to the boilers, resulting in better circulation in them, which also helps to keep down corrosion. On the other hand, the very conditions under which economizers work are peculiarly favourable to corrosion, viz. low water velocity, low alkalinity (no concentration taking place as in boilers), and the heating influence tending to liberate dissolved gases. Feed-pipe pitting is frequently a troublesome matter, and here again the cause is much the same as in the case of economizers. With regard to steel turbine-blades, there is a tendency for corrosion to take place when the machine is standing. To avoid this by means of drying the blades, a well-known firm have adopted the practice of passing air through the machine when stopping and immediately after shutting off steam, the air being induced through from the high-pressure end by the condenser vacuum. Turbines, like boilers, probably suffer at least as much damage while standing as when working. Some time ago I had experience of a turbine which had been lying idle for several months while its condenser was used for another machine. When the turbine, which had been thus idle so long, was ultimately opened up, its steel blading and wheels were found to be in a very bad state of corrosion, but the bronze blading was quite good. By comparison with other similar machines not so treated, it was clear that the severe corrosion above referred to was due to the unfavourable conditions, in an atmosphere of vapour, etc., to which the machine had been subjected. To keep the blades dry while standing seems to be the ideal method in order to avoid corrosion.

Mr. C. L. MacCarthy: One of the most interesting cases which has come before my notice in connection with the corrosion of steel pipes was an 8 in. rising main installed in a pit shaft some 14 years ago, the water being pumped by means of a steam pump at the bottom of the shaft into a lake at the surface. About 5 years ago an electrically-driven pump was fitted, together with an entirely new line of pipes, the existing steam pump and rising main being kept as a stand-by. The new pipes corroded through in the bottom section in 4 years. The matter was thoroughly investigated, and the only explanation, as the pipes and water were identical in both cases, was that the trouble was due to stray currents. Another interesting case was a compressed-air main in a Lancashire colliery. This main was installed some 7 years ago, and on being examined about a year ago it was found to be badly corroded internally. On investigation the trouble was ascribed to acids in the oil used in the compressor. The main in question was of 10 in. diameter, and it was the first section at the top of the shaft which was chiefly affected. Similar steel mains which have been working in the same district and have been installed many years are unaffected, pointing, as it was afterwards proved in the case referred to, to purely local conditions. With regard to feed pipes, I have of course come in

touch with many badly corroded mains and the chief trouble undoubtedly is, in the majority of cases, due to gases. It is not uncommon to find that at two works in the same town with feed mains working under exactly similar conditions, in the one case the main has been badly attacked while at the other works it will be in excellent preservation. With pipes laid in earth the life of the main depends chiefly on the protective coating. The great point in laying pipes is always to see that the coating is not damaged. An extra precaution which is often taken is to coat, wrap with canvas, and re-coat, the canvas protecting the solution from damage.

Mr. R. C. Atkinson: The last speaker has rather hinted that one of the most potent causes of corrosion is stray currents. I rather join issue with him on that as he is interested in the working up of metal, and I take particular note of one sentence in the author's paper, with which I am in entire agreement. He says on page 119, "Iron and steel may be regarded as complex mixtures." I think a lot of the trouble we suffer from in corrosion is attributable to our neglect of that fact. We treat iron and steel in a very casual fashion. Think how metal plates and sections are treated during manufacture into articles, how they are not subjected to really scientific heat treatment or anything of that sort. Take the flanging of plates—they are heated up in a furnace to a certain vague temperature which is judged entirely by the eye of the man in charge. There is no scientific method adopted to ascertain whether a certain definite temperature has been reached before the plate is flanged—they get through what they can in the one heat, if not they have a second; if they are nearly through they try to get it through in the one heat to save heating it up a second time. As a result the metal is subjected to serious stresses. Some time ago I made inquiries among some of the leading boiler-makers as to the methods they adopted for seeing that plates were subjected to a proper temperature before work was done on them, and further, that they were properly annealed afterwards. I was astonished to find that not one of the boiler-makers used any means for determining with accuracy such temperatures. They all relied on the experience of the men in charge. Most of us know that iron workers and metal workers, particularly those who have spent their lives in the manipulation of iron and steel at varying temperatures, have very great skill in judgment by the eye as to the proper temperatures, but that to my mind is a very unreliable factor because the human element enters in. All those things tend to the metal not getting fair treatment, and when, as the author has pointed out, internal stresses are present in the metal we get potential centres of corrosion, and I think it is up to the manufacturers in this country to pay very much greater attention to the treatment they give to the various metals which are used in engineering work. I think when we get down to a more regular and more scientific treatment of the metals corrosion troubles will be very much reduced. On page 120 the author says that in future "The time is fast approaching when engineers will specify the constituents of castings, including pipes." I think that is highly desirable. On the other hand, it is very difficult to get manufacturers to make anything to definite specifications. With regard to the condenser-tube ferrule question, the author suggests that the corrosion is entirely due to air and the oxide of iron in the water. I would ask him whether he does not think the lubricant in the packing may have something to do with it. The packings in condenser tubes are boiled in tallow, which is of animal origin. We may get some acids liberated there which may have some effect on it. With regard to turbine blades, I would suggest to the author that some of the trouble is due to erosion. Where we have reached the dew point we get water travelling at a high velocity. It may be that the wasting away of the blades is due to erosion by this water and not entirely to corrosion. With regard to the protection of corrugated sheeting, some time ago the French Government set up a Commission of Engineers to inquire into the best method of protecting galvanized corrugated sheeting. The solution they finally arrived at was that neither tar nor paint, by itself, was any good. If we paint the corrugated sheeting that is soon attacked. We get through the paint on to the galvanizing, and that is attacked in the way the author has pointed out. If we used tar alone, there is sulphur in it and that attacks the galvanizing. The solution was that we should paint the galvanized sheeting with two coatings of paint and then put tar on. In this way we get a perfect protection of the galvanized sheeting.

Dr. W. H. Hatfield: The author advances the electrolytic theory of corrosion, and I largely agree with him. The theory serves very well as a general explanation of the corrosion data which have come to my notice as a result of the systematic study of the corrosion of ferrous metals. There are, however, several anomalies which require further study. In particular, several speakers have referred to the relative behaviour of wrought iron and steel. To me the matter is summed up something like this. Wrought iron may vary much. We may have a specimen of wrought iron which is all ferrite, or we may have a sample which is high in silicates and possibly in phosphorus. We should expect to find a disparity in the behaviour of those wrought irons. Comparing steel and wrought iron, the author has shown how, as the carbon contents increase, the pearlite constituents also increase. True steel is a steel containing 0·90 per cent of carbon and consisting of pearlite. It follows that with a constituent of the structure which he has illustrated we should expect corrosion, according to the electrolytic theory, to take place at a much more rapid rate than in iron which does not contain it. There is another important factor which enters into the corrosion of commercial steel; that is the presence of manganese. Siemens steel, Bessemer steel, in fact all commercial steels in the method of production have manganese added to them to ensure soundness and good working under the press. The presence of this manganese greatly increases the tendency to corrode. I was very glad to see that the author emphasized the effect of defects and segregation upon corrosion. Also in rolled or forged steel we sometimes have laps—a piece of rough steel is hammered into the bar or forging, carrying with it a surface of scale. That is one example of defect. Wherever there is

segregation, or silicates and oxides mechanically introduced in the manner I have described, they become seats of corrosion. It seems to me that engineers should make a special point of seeing that, as far as possible, the steel they use is free from segregation and defects generally. I agree with the author that terms such as " cast iron " and " steel " are quite loose. Whenever I have the opportunity I always make a plea that engineers should give more attention to the science of steel. The suggestion by one of the speakers that the turbine should be dried by passing air through it seems to me to be an extremely good plan. In some of our experiments we have noticed that where a liquid, a dilute solution, would not bring about corrosion, if we left a drop of that liquid on the specimen corrosion took place. As the drop evaporates, a concentrated solution of the acid or whatever it is in solution is produced. In the paper it is suggested that the physical and mechanical properties of stainless steel are not comparable with those of other high-tensile steels. I should like to take this opportunity of removing that impression, and in this connection I will refer to the figures in the accompanying table. The last speaker emphasized the importance of accurate heat treatment, and this table shows how important it is that the actual temperature should be ascertained. It is interesting to note that several works have used stainless steel for turbine blades. In one instance after $2\frac{1}{2}$ years' service there has been no corrosion and no erosion.

STAINLESS STEEL

Size, $1\frac{1}{8}$ in. round × $7\frac{1}{2}$ in. long.

Treatment		Yield Point	Maximum Stress	Elongation	Reduction in Area	Hardness (Brinell)	Izod Impacts
Air Hardened	Tempered			Per cent	Per cent		Ft.-lb.
875° C.	1 hr. 500° C.	70·9	85·9	13·0	40·5	3·12	—
875° C.	1 hr. 600° C.	44·5	53·6	21·0	59·2	3·9	69, 73, 69 and 59
875° C.	1 hr. 700° C.	31·6	45·2	26·0	64·6	4·25	86 + 3, 86 + 13, 86 + 17
875° C.	1 hr. 750° C.	29·5	43·9	28·0	63·6	4·25	86 + 16, 86 + 26, 86 + 25
875° C.	1 hr. 800° C.	31·6	43·3	27·0	64·7	3·7	33, 33, 43

Mr. A. R. Chaytor: At the top of page 120, the author suggests that a " Clayey character of soil leads to an increased retention of the electrolyte," and advises that the pipes or cables be surrounded with sand in preference to clay. I am of the opinion that, where the bottom of the trench does not exceed the depth of the clinker or ash subsoil, it is better to surround the pipe or cable completely with moistened clay, well rammed. By doing so, the pipe will be securely sealed against any access of the electrolyte, and a free drainage space will be left around the pipe. In cases where the trench is excavated through clinker and ash into a clayey stratum, it would be strongly inadvisable to surround the pipe with sand in preference to clay; for the sand would then act as a drain from the upper layer of ash. On page 125, it is suggested that " Exterior corrosion and solvent action of water on lead pipes may be due to salts in the soil, or the action of organic acids in the water flowing in the pipes." I should like to hear how the author accounts for this action. I recently heard a colliery engineer complain of the more rapid corrosion of the winding ropes since the installation of electrical power into his colliery, and as I found on inquiry that the power was all three-phase alternating current, I could only conclude that it was another case of prejudice. It is also remarkable what a large number of gas engineers are still of the opinion that three-phase lead-sheathed and armoured cables are injurious to, and the cause of electrolytic trouble on, pipes in the vicinity. The fracture and breakdown of pin-type insulators due to the corrosion of the metal pin and its consequent expansion is becoming a rather serious problem, and it would be interesting to know whether " rust-less " steel or any of the modern alloys could be commercially adopted to avoid this trouble.

Mr. E. C. Balmford: On page 121 the author refers to the stresses in iron and steel resulting in corrosion. In connection with this it may be of interest that, when in conversation with one of our leading pump makers a year or two ago, I was shown two gunmetal impellers from turbine feed-pumps, one of which was very badly corroded at the tips and the other, which had been running a longer time, was in perfect condition. The latter had been running in greasy water, and it had been protected by a very slight film of grease which had collected on it. They expressed the opinion that the corrosion on the former impeller was not a chemical one but was due to the difference in stress in the metal at the periphery of the impeller and at the centre, which set up internal currents and led to corrosion. They also referred me to experiments which had recently been conducted in which two bars of gunmetal of exactly the same composition were immersed in electrolyte, and on one of the bars being put in tension there was quite an appreciable electromotive force set up between them.

I should like to know if the author's experience confirms this.

Mr T. B Johnson: The question whether the pipes and cables were damaged, quite apart from electric currents, is of so much importance that I should like to ask whether the author definitely satisfied himself that no electric currents got into the cable and the pipe. Of course if a leakage current could have been present, as for instance, in the case of the tramway standard which was not bonded, then the cable would make such a good conductor that it would be very likely indeed to be attacked. On page 120 the author says that "Lead pipes should be enclosed in wooden casings and not exposed." I take it that means where lead pipes are laid underground and that no objection is seen to the provision of exposed lead cables along walls, etc., in buildings. On page 121 the author says that "It has been noted by many observers that corrosion of steel is not accelerated by contact with other metals or alloys." In view of what he says elsewhere in the paper it seems surprising that such is the case. All the elements of an electric couple seem to be there, and I should be glad if he would explain why these joints are immune. Lastly I would suggest that he might amend the title of the paper to read "The Effect of Air and Water on *Metals* used in Engineering Work."

Dr G. D. Bengough (*communicated*): I propose to deal only with those points about which my experience appears to differ to some extent from the author's. In the first place I believe that, from the practical point of view, too great stress has been laid on the initial electrolytic action that may occur when metals are placed in certain liquids. In many cases the initial action is not the most important factor in determining the position of the pits in which engineers are very justifiably and specially interested. The initial action, whether it be electrolytic or not, merely gives rise to a general roughening of copper, brass and many other types of non-ferrous materials. It appears to be secondary actions, probably of a chemical nature, which give rise to the really troublesome local actions that result in pitting. Such actions are particularly violent when there is chloride in the water. The fact that rust is not only a sign that corrosion is proceeding but may also act as a local accelerating factor under many conditions, provided it has not been dried, seems to have escaped the attention of many authors and others interested in corrosion, yet it is one of the most important factors of all in accounting for local pitting. Once an accumulation of rust has been formed at any point on a piece of iron or steel, whether by natural or by certain artificial means, local action will tend to take place at that point under many sets of conditions. In other words it is not necessarily any local variation in electrical properties of the original metal that gives rise to local pitting, though it may sometimes be so. It seems to me that too great concentration of attention on the electrolytic view of corrosion is liable to cause many factors of great practical importance to be overlooked. An example is the corrosion of condenser tubes in waters that contain chlorides. In such waters deposits of even the purest samples of rust and cause very serious corrosion under many sets of conditions. Yet the electrolytic view of corrosion in the form in which it is usually stated certainly does not suggest that any such action would take place. In certain other types of water which contain no chloride, but which are quite good electrolytes owing to the presence of carbonates, no such action takes place. I should be much interested to hear how the author would explain these facts in view of the nature of corrosion which he outlines in the earlier part of the paper. I should also like to ask him how he explains the fact that potassium bichromate, which is known to be a thoroughly good depolarizer and is used as such in certain primary cells, inhibits the corrosion of iron, copper, zinc, and other metals. This set of facts hardly seems to be in good agreement with the statement on page 119 that "any substance which dissolves or reacts with hydrogen accelerates corrosion. This is found in practice to be universally true." I have met many other experimental facts in my study of corrosion which cannot be easily harmonized with the view that primary electrolytic action is the cause of the numerous troubles that occur in practice. They do not disprove the electrolytic view of corrosion, but they indicate quite clearly, in my opinion, that it must be supplemented by the recognition of secondary reactions, which are of great technical importance.

Mr. G. R. Hingelberg (*communicated*): Messrs. John Brown & Co. had some 10 years ago in their old power station a condensing plant which included a cooling tower, the circulating pump being of cast iron with a bronze impeller. One day the pump would not perform its duty and, on opening it out, we found the cast-iron casing all coated with bronze and the impeller considerably reduced. We came to the conclusion that it was caused by electrolytic action due to the difference of metals and a peculiar feature of the circulating water. This water, of course, was used over and over again, and in passing down the cooling tower (which was of the fan type) the water picked up the sulphur fumes, of which the air is full in that particular part of the works, and was turned into sulphuric acid. On making an analysis of the water we found that this was the case, and we have had to treat the water ever since so as to make it slightly alkaline.

Mr. J. W. J. Townley (*communicated*): I have sent for inspection by the author a corroded condenser tube which is, I think an excellent example of de-zincification caused by electrolytic action, and I should be glad to have his comments upon this case. The circumstances are as follows. Five tubes in a turbine condenser failed after they had been in use about 12 months. The circulating water was tested and found to be decidedly acid due to concentration in the ponds. The water was then treated with soda ash until a slightly alkaline reaction was obtained with phenol-phthalein, and all make-up water was treated in the same way. Several tubes have failed since this treatment was adopted, but it is believed they were affected previously. New tubes after two months' run show no signs of corrosion when they are withdrawn and there is a tendency for scale to form on the tubes and tube plate, which previously showed clean surfaces with patches of corrosion. When the first tubes failed, a number were

withdrawn for inspection and a selective action was noted, as several were quite free from corrosion and others badly pitted. On page 118 the author says, "When the acid solution is entirely neutralized by, say, an alkali, the process is arrested"; so presumably in this case as long as the cooling water is kept neutral or alkaline the electrolysis is arrested.

Mr. H. E. Yerbury (*in reply*): In reply to Mr. Campion's remarks regarding wrought iron for boiler feed-pipes, it is generally found that this metal is not so reliable as cast iron, and his trouble due to corrosion of pipes conveying water to boilers would, I think, be minimized by using cast iron. In connection with two pumps working under what appear to be the same conditions, when only one pump is injuriously affected, all details must be studied, and it will probably be found that certain minor conditions are present in the one case which affect the rate of corrosion. Even the difference in working head has been found to be a cause of corrosive action, and by increasing the head by partly closing the discharge valve, and thereby retarding the liberation of air in the impeller and pump body, corrosion has been arrested. The problem of condenser tubes and means of extending their life is still a subject of experimental research and each case should be studied individually, special attention being given to the quality of the water (especially the matter in suspension, temperature, speed of flow, and general condenser design).

In reply to Mr. Christianson, it is unfortunately true that most steels corrode more readily than wrought iron, for reasons stated in the paper, and it is interesting to hear that wrought iron is superior to steel for pump shafts running in polluted salt water. Regarding the effect of erosion as distinct from corrosion on pump impellers, etc., speaking generally it may be said that where erosion only has taken place, thus producing a scouring action, the composition and structure of the remaining metal are unchanged; whereas, with electrolytic action, the composition and physical properties of the original metal will have been altered to its detriment, as corrosion takes place principally at the crystal boundaries. It has been found that condenser ferrules are sometimes made of yellow brass instead of Admiralty mixture (70/29/1), in which case de-zincification often takes place and they become brittle. Regarding the use of pure feed water for boilers, I am informed by the general manager of the Detroit Edison Company, where a closed system has been in service for many years, that no corrosion or pitting has occurred and that the town's water occasionally used in the surge tank, or in filling a boiler, has been sufficient to give the boilers a slight protective covering such as would be obtained from a thin coat of whitewash. It will be readily seen that under such ideal conditions boilers could be safely worked up to at least double their normal rating. With or without a closed system it is always desirable to keep feed water very slightly alkaline. The practice of drying the blades of turbines by passing air through the machine after steam has been shut off is an excellent plan to avoid corrosion.

In reply to Mr. MacCarthy's remarks on corrosion of 8-inch steel pipes in a pit shaft, I am inclined to think that the cause could not have been thoroughly investigated if the explanation of the trouble was summed up by the stray current theory. It should be remembered that current leaking to a pipe line does not injuriously affect it, and it is only where the current leaves the metal in the presence of an electrolyte that damage can be done. The water in a colliery rising main would doubtless contain air and corrosive matter in suspension or solution, and cast iron would be preferable to steel pipes under these conditions.

In reply to Mr. Atkinson, it is regrettable that metallurgy is not studied sufficiently by engineers and ironfounders and general manufacturers, and it is hoped that more scientific methods will be adopted in the near future. When it is found that good results follow accurate working to a specification, doubtless greater willingness will be shown by founders and others to meet engineers' requirements. With regard to oil in condenser-tube packings, it is well known that animal oils are acid and therefore corrosive, but in many instances where dry cord impregnated with graphite was used as a packing and no oil was present a pitting action was set up. Erosion is a factor in the useful life of metals which is receiving careful attention by metallurgists, and finality has not been reached in the evolution of alloys to withstand such erosive action. Analyses clearly show whether a certain action is due to erosion or corrosion, and, as Mr. Christianson pointed out, much damage has been caused to turbine blades when a machine has been standing, in which case pitting and corrosion only could take place. The life and protection of galvanized sheeting largely depend on climatic and local conditions, and the method adopted by the French Government is undoubtedly a good one. It is generally found that any composition of a neutral character which covers metal and remains impervious to moisture will act as a preservative. In certain cases where the galvanizing is very smooth a rougher surface may be formed by brushing on a solution of copper salts over which the paint or tar film is more adherent.

I am very pleased to hear from Dr. Hatfield that stainless steel is now being used with success for turbine blades and that its physical properties are better than were suggested in the paper. As shown in Dr. Hatfield's test results the physical properties are enormously affected by heat treatment, and I think the success of this chromium steel is assured when it is properly hardened and tempered to suit the purpose for which it is supplied. It is, I think, advisable to mention that this steel has its limitations and that it is possible to start corrosion if gunmetal is in contact with it in salt water, or if an oxide of iron is in contact with it in the presence of an electrolyte. Under any working condition the tendency to corrode is far greater when the metal is in the rough state than when it is polished. Engineers are familiar with corrosion on steel poles and, as Dr. Hatfield points out, the manganese constituent accelerates this action. It is therefore advisable to specify poles and structures to be low in carbon and manganese. I note that Dr. Hatfield largely agrees with the electrolytic theory of corrosion.

In reply to Mr. Chaytor's remarks, it has been found

that clay invariably retains water, which is the main factor in starting corrosion. Clay often contains soluble salts such as magnesium chloride and nitrates, calcium sulphate and bicarbonate, which tend to produce a good electrolyte. If pipes are laid in sandy soil the water percolates through and is not held as it would be in soil of a clayey character. If it is possible to seal the pipes securely with well-rammed clay as Mr. Chaytor suggests, I agree it is good; but when laying pipes through ash and clinker, I think that concrete should surround them. In connection with the sentence on page 125 quoted by Mr. Chaytor, the solvent action of certain waters such as peaty water containing humic acid is well known, especially on lead pipes. Lime is recommended as an antidote. I am not aware that rustless steel has been used for insulated bolts and studs on pin-type insulators, but I think it would be quite suitable for that purpose. Where the insulators are not subjected to a big strain, high tensile bronze would prove satisfactory.

In reply to Mr. Balmford regarding the theory of "internal" currents being set up in a casting such as a turbine pump impeller due to the difference in stress between the centre and the periphery, my experience does not confirm that theory. It is, however, generally agreed that when metal is stressed, a higher potential will be set up in the presence of an electrolyte than on an unstressed metal. In other words the stressed metal assumes a positive potential to the negative potential of an unstressed metal, but I should not regard this as an "internal" current. The film of grease deposited on the impeller which was unaffected would appear to insulate the metal from the action of the feed water. The tips of impellers are usually affected before the hubs, as vacuous spaces are formed and air is liberated tending to invite corrosive action. It has also been shown by the Hon. Sir Charles Parsons that by closing up vortex cavities high pressures might be generated and pitting brought about by this sudden collapse in which case the crystals of the metal would of course be shattered. Water-hammer is undoubtedly produced by this action.

Regarding Mr. Johnson's remarks on damage done to underground pipes and cables and the specific instance mentioned in the paper, a slight rail leakage current was indicated from the tramways, but an almost equal but steadier potential and current existed when the trams were not running. The Sheffield Gas Company satisfied themselves by a two years' test on pipes where a current from a battery was connected, that no difference in the rate of corrosion occurred in various qualities of soil and moisture between the "charged" pipes and those not connected to an external electromotive force. The nature of the soil and electrolyte largely determines the useful life of metals. The enclosing of lead pipes in wooden casing is recommended only where laid underground. Regarding the rate of corrosion of steel in contact with a non-ferrous metal, lengthy experiments have been carried out in this country and America and deductions indicate that contact between ordinary steel and bronze and between steel and other metals neither promotes nor accelerates the corrosion that normally takes place in steel alone. To give one instance: it is well known that on board ship brass nuts are used on steel bolts and can be screwed off after many years' service, whereas a steel nut on a steel bolt would soon be permanently fixed by corrosion in salt water or an intermittent salt spray.

I quite agree with Mr. Johnson that the title of the paper might be amended. I was hoping to include various other materials in addition to metals, but found that the subject matter would be extended beyond the limits of an Institution paper.

In reply to Dr. Bengough's communication, apart from corrosion research I think that it is not the initial electrolytic action or skin effect on metals that interests engineers so much, as the subsequent action which often produces ultimate destruction of the material. Dr. Bengough appears to draw a line of demarcation between electrolytic and chemical processes. I incline to the idea that all chemical forces appear to have an electrical origin and chemical reactions are purely reactions of ions. For instance, in the case of a salt, chloride of zinc ($Zn^{+}Cl_{2}^{-}$), the zinc atom has, I think, a positive charge of sufficient magnitude to hold in equilibrium two negative ions of chlorine. Neither chemical action—electrolysis—corrosion nor oxidation can be started without a disturbance of equilibrium, hence the nature of the electrolyte is all important in the study of the subject. The instances cited of the action of water containing chlorides, carbonates, and potassium bichromate with their dissimilar characteristics are interesting from the electrolytic standpoint. A soluble salt is, I think, made up of a combination of a positive and a negative ion. Acids and chlorides in solution contain hydrogen ions which are the attacking ions. These are electro-positive to oxygen, whereas all substances which develop hydroxyl (electro-negative) ions in solution, such as alkalies and carbonates, inhibit corrosion and rusting. The statement that "Any substance which dissolves or reacts with hydrogen accelerates corrosion," I venture to think is correct for the following reason. When equilibrium is maintained between a metal and the film of gas or electrolyte surrounding it, no corrosion will take place. The absence of equilibrium is generally brought about by the removal (by various means) of the substances which would keep the metal in a passive condition. It will therefore be seen that a neutral or negative agent which does not remove the hydrogen with its positive charge from the surface of the metal which is made negative by its solution pressure inhibits corrosion. Oxygen, for instance, which reacts with hydrogen accelerates corrosion. I agree that secondary reactions are most important, and I submit that both primary and secondary actions conform to the electrical hypothesis. Regarding the action and properties of rust mentioned by Dr. Bengough, I look upon an oxide of iron as an electro-negative element, and corrosion invariably starts by its presence (even on polished stainless steel), as ordinary rust is very porous and usually contains a considerable quantity of water. As mentioned in the paper, when a nodule of rust is formed or deposited, it retains the electrolyte, thus forming the negative element to the positive matter near it and corrosion is

started. A dry oxide has no injurious effect. Similar results are often brought about by foreign matter such as sand, which Dr. Bengough mentions. This has a tendency to absorb and retain a concentrated electrolyte, thus increasing locally the normal activity of that particular liquid. I submit that lodgements of sand or coke act in the same manner as the packing on the condenser tubes cited in the paper. From the electrolytic view I should expect chloride of sodium to be one of the most active agents of corrosion, and carbonates to exert certain protective actions. There are many anomalies connected with the subject of corrosion which require further elucidation, and Dr. Bengough's researches will, I feel sure, be keenly studied by engineers. I hope that definite conclusions will be forthcoming regarding the prevention of corrosion.

Mr. Hingelberg's communication confirms the point made in the paper that cooling-tower water may have highly concentrated characteristics and do much damage to pumps and the general water-pipe system. It is interesting to hear that on treating the acid water and making it slightly alkaline, trouble has ceased at Messrs. John Brown's works.

I am not in a position to confirm Mr. Townley's opinion that the trouble on his condenser tubes is ended, and I would recommend him to read the Reports of the Corrosion Research Committee which are now published. His treatment of acid circulating water with soda ash will produce a carbonate scale on the tubes, and this forms a resistant surface film which undoubtedly has an inhibiting effect on corrosion. Unfortunately this surface layer of carbonate slightly affects the heat transference and it is generally scoured off when the tubes are periodically "rodded" and cleaned, hence the desirability of neutralizing any acidity present in the water.

CO-ORDINATION OF RESEARCH IN WORKS AND LABORATORIES.

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I. Synopsis.

In this paper an attempt is made to introduce to the authorities dealing with the reconstruction of our national industries after the war a further problem which is intimately connected with reconstruction but which has up to the present remained undiscussed, namely, the co-ordination of research in laboratories attached to universities, colleges, and technical institutions, in laboratories working independently on commercial lines, and in the experimental departments of manufacturing concerns. In the past there has undoubtedly been an enormous amount of overlapping in the work done by such laboratories, and it is felt that the time is now specially opportune for making a change in the direction of co-ordination and combined organization, in order that these experimental laboratories may be run at the maximum national efficiency.

At the outset are put forward arguments to show the vital importance of this neglected question and the practical necessity of co-ordination if we are to meet successfully the after-the-war competition of foreign manufacturers, mention being made of how other countries stand in this respect. A scheme is then proposed in which all the existing laboratories of the country would be united under one roof; but immediately afterwards this idea is shown to be impracticable. As an alternative a scheme is propounded whereby the present laboratories are retained in their existing form and the co-ordination consists essentially of skilful organization through a central board of control. After showing that this scheme is no utopian one, but is perfectly feasible, further details are given of the proposed constitution and working, exact particulars being mentioned of the relationship between the board and the laboratories, as well as the inventors of the country. Finally, conclusions are drawn and the wish expressed that some scheme similar to the one outlined may become an actual reality of the near future.

II. General Considerations.

Introduction.—In July 1914 the whole civilized world was living more or less in a state of comfort and ease, congratulating itself the while that in all respects it was more civilized than any of its forerunners. Then came the great cataclysm which for the last four years has made us all remodel our creeds and ideas, causing us to adapt our lives to the conditions inseparable from war. Latterly our thinking men have begun to point out that the present state of affairs cannot last for ever, and have been asking us to prepare for the time which will dawn with the declaration of peace. They state with truth that this war will be followed by a second one, whatever the terms of peace may be, and that, moreover, this after-the-war struggle will be just as keen and fierce as the present one. The weapons thereof may not be as murderous and death-dealing as those employed on the battlefields of France to-day, yet in the guise of trade competition in all corners of the globe they will be just as sharp. Victory will mean life, whilst defeat will mean national stagnation and even the downfall of the race. Whatever the military and political result of the present struggle may be, the real victory will lie with that side which finds itself best prepared for the forthcoming commercial war, and which can recover its financial position most quickly by means of its home and export trade. Germany will strive harder than ever for commercial supremacy, and therefore it behoves us to leave no stone unturned to be ready to meet her when the time comes. "Be prepared" must be our motto in all industrial and commercial problems.

The present age is one of progress and especially of scientific progress. The days are gone when the greatest nations were known for their hunting prowess, their sense of the beautiful in nature and architecture, or their intellectual writings. To-day to be a great and prosperous nation implies to be at the forefront in scientific genius, in engineering capacity, and in the capability of harnessing or ordering the immeasurable forces of nature for the benefit and convenience of mankind at large. There was a time when this country

was able to hold its own against any other nation in all branches of science, but the opening years of the present century found us rapidly falling asleep and allowing our present enemies to take our place. Fortunately the events of the past few years have made us open our eyes to our danger, and it may be said that, if this war has any redeeming feature at all, it is that we have as a nation been saved from ourselves and have realized how near to the precipice we were. The lesson has been a costly one, bought not only at the greatest imaginable financial cost, but also with the blood of the Empire's manhood. If we even now refuse to learn the bitter lesson, then all the sufferings and sacrifices of our boys on the battlefield will have been in vain.

Importance of organization.—The reasons for our thus gradually losing our commercial supremacy are not to be found in any lack of ability or want of inventive genius, because we have never been without our great industrial leaders and our inventors. We have had, and still have to-day, brains which are equal to those of any other country in the world. Nor is the deficiency caused by any incapability to carry out the work prescribed by the brains of the nation. The British workman is universally recognized as being without his equal in practically every branch of industry. In other words the material has been there all the time and our back-sliding has been entirely due to lack of responsiveness to scientific genius by our responsible government authorities, our manufacturers, and our financial leaders, as well as to the absence of organization. Many examples could be given of new ideas or inventions devised by British brains which have met with absolutely no reception in their country of origin and have therefore as a natural sequence been taken abroad, in many cases to be eagerly picked up by our present enemies, as we have since learned to our sorrow. If we had been better organized, if our financial and manufacturing leaders had supported the men of brains, then many such new ideas would now be in British control and we should have continued to lead the world instead of gradually giving place to Germany.

Turning to the other side of the question, we find that German brains are in reality not superior to our own as far as the creation and development of new ideas are concerned. It was only through their better ability to recognize at a glance the importance of new designs or methods, that they were getting ahead of us. We have heard a great deal during the last few years about the engineering and commercial supremacy of Germany, but after having lived on the Continent for over five years, and after mixing with scores of Germans of all classes and especially engineers, the author would emphatically state that their average intelligence is no greater than that of a batch of similarly-situated Englishmen. As a result of improved methods of education with special reference to science and engineering, the knowledge may be greater or wider, but the actual intelligence or genius is certainly not superior. The only real advantage which the German firms have had in the past over British competitors lay entirely in the capacity for organization and the recognition of the possiblitity of raw ideas in order to develop them for the benefit of the German people as a whole.

At the same time it must be stated that this capacity for organization is not entirely inborn, but is mainly the result of intensive training and development during the past two generations. It therefore stands to reason that, if we had gone to the same trouble, we could have become at least as proficient in the art. This has been proved time and again during the present war, when the whole nation has been faced with innumerable problems of apparently insurmountable difficulty and of unprecedented magnitude. With one or two deplorable exceptions we have come out victorious every time, showing initiative and organizing talent which has astonished our critics and which has sometimes been described as being worthy even of our enemies. The "writing on the wall" states clearly to-day that we must not let this newly-found talent drop into disuse, but must apply it with an even increased vigour to the stupendous after-the-war problems which are already beginning to face us.

Individualism v. Collectivism.—It was stated above that the German organizing capacity was devoted to the good of the German nation as a whole. This is a most important point and may be considered as the crux of the whole question. The German people, whether willingly or as the outcome of its educational system, or compelled by force akin to militarism, has been taught to sink self for the common good, to sacrifice individualism for collectivism, to put the "Vaterland" before self. Examples of this fact are numerous, but it will be sufficient to mention the way in which the smaller manufacturing concerns have allowed their personalism to be merged into the collectivism of great trade combines, for the purpose of conquering the world's markets for the benefit of the nation as a whole. The Britisher, on the other hand, has as an individual been so proud of his own prowess as to want to fight all his own battles, being at the same time too stubborn or selfish to communicate his methods of working to his fellow-workers in the never-ceasing struggle for commercial supremacy. This individualism is to a large extent due to our insular position and to the life of comfort and ease which we have, as a nation, enjoyed for over a century. Indeed, to be independent is in many respects a praiseworthy constituent of a man's character, but *tempora mutantur* and if we don't adapt ourselves to changed conditions, we deserve to get left behind in the race.

During the present war we have all been to a greater or less extent forced to sink our individual independence in the national cause and to give up for the time being our personal freedom. We are bound by so many different ties to our fellow-countrymen, that we cannot give rein to our old selfish instincts even if we wanted to do so. After the war we hope to regain our individual independence, that being of course the whole reason for the recent struggle in France, but at the same time we must not expect to be able to throw off all the fetters of collectivism, because the world will be a changed place afterwards and old standards of life will no longer be applicable. Certain of the bonds

which bind us to our fellow-citizens will and must remain as being necessary for our continued existence as a nation. One of the greatest of these remaining bonds will be that of commercial organizations where the individualism of the separate firms belonging thereto must be sacrificed to a certain extent in the interests of the members as a whole.

In this connection it should not be forgotten that by such co-operation the interest of the individual will not actually suffer. The opposition to such co-ordinated action always exists before formation, or at any rate only for a short time afterwards, because the whole idea is based upon the hypothesis that the individual cannot succeed and is bound to meet with failure if he stand alone. Whilst the main object of such co-operation lies in the immediate welfare of the nation as a whole, yet the ultimate prosperity of the individual is bound up therewith. A successful nation implies success among its component citizens, and, conversely, prosperity among the industries involves a prosperous nation. Although, therefore, individuals and companies may hesitate about uniting themselves for combined action, yet such hesitation must spring entirely from temporary selfishness or shortsightedness, because the resultant national good cannot help but rebound upon the individual.

Co-ordination in research.—Apart from the co-operative efforts arising out of or in connection with the war, the past two years have seen the birth of many combinations of interests for the sole purpose of strengthening and extending the trade of the country after the war. We now have several powerful banking amalgamations to offer a stronger financial front against external competition, numerous unions of workmen to protect the rights of the individual worker, and various associations of employers to further their different businesses. Among the latter are to be found financial combines to assist the weaker members in times of monetary stress, manufacturing associations to prevent too keen a competition and too much overlapping between the different works, to say nothing of the co-operative selling organizations to simplify and cheapen the getting of orders, especially abroad. In every case the fundamental principle underlying the co-ordination is to be found in the words "unity is strength."

But amongst all these co-operative organizations we must look in vain for the slightest approach to any real co-ordination as far as research into new and improved principles or better methods of manufacture is concerned. It is true that quite recently the Privy Council appointed a Committee for Scientific and Industrial Research which received a grant of £1,000,000, took over the National Physical Laboratory, and is at present carrying out researches on the production of tin and tungsten in Cornwall; also that a National Fuel Station has been established at Greenwich, that a British Scientific Instrument Research Association has been formed, and that several other minor attempts at co-ordinated research have been made, but nevertheless each individual manufacturer is still content, generally speaking, to jog along on his own, too independent or too proud to seek the help of his fellow-workers. Surely, if co-operation has proved itself to be beneficial and essential in the fields of production and distribution, it is only logical to assume that co-ordination in the preparation of ideas for production would also be advantageous and is indeed necessary to our national trade, in order that our resources in men and materials may be utilized to the best advantage and in order that there may be no wasteful overlapping. Unfortunately, the need is not yet generally admitted, and therefore it would perhaps be advisable to go into this question more closely, especially in view of the fact that after the war the shortage of men, equipment, and materials, will become a still more important factor.

It has been pointed out that we live in an age of progress, especially of scientific progress, and that the race for commercial supremacy between the countries of the world after the present war will go to the fittest in this respect. It is a question not merely of being a scientific nation, but of being a progressive one. We must never allow ourselves to be caught napping again, and we must always be on the look-out for new principles, new applications for those already known, new spheres of use for the same, new materials and new articles. What is more, we must know how to use these new ideas when found. Our whole future national economic life is dependent, to an extent as yet hardly realized, on our making continued scientific progress.

Having thus shown the importance and vital necessity of co-ordination of research, it is now proposed to see how these can be carried out in the most satisfactory manner. At the outset it should be stated that the solution of the problem is beset with innumerable difficulties, there being so many conflicting interests to be propitiated. Nevertheless, as already pointed out, we have in this country the necessary men to carry out the work, as well as a great deal of the needed material equipment, and it is therefore only a question of deciding upon the most suitable organization and of setting up the machinery to look after the same. It should perhaps be stated that it is only proposed to deal here with co-ordination of research as far as technical science and engineering is concerned. Naturally every other branch of industry and science, such as cotton-spinning and medicine, could be similarly treated or indeed afterwards embodied in one great national scheme, but such branches lie outside the scope of an engineering institution such as ours and must therefore be left to be taken care of by their own experts.

When dealing with national questions of this nature, it is usual, especially at the present time, to see what has already been done and also what other countries are doing in the matter. Turning first to America, we find that there is no real co-ordinated action as regards research, although each of the large manufacturing concerns is particularly well-situated for the carrying out of extensive experimental work, the American General Electric and Westinghouse Companies being two of the most noted in the electrical industry. Similarly in Germany there is no real co-operation in research, although the Germans are otherwise very wide awake to the advantages of co-ordination, unless the huge experimental departments of such firms as

the Allgemeine Elektricitäts Gesellschaft and Siemens Schuckert are considered as combines for this purpose. Before the war every German manufacturing firm, even the very smallest, had its own well-equipped laboratory with a whole-time experimental engineer and chemist, but, nevertheless, extreme secrecy and jealousy was the rule as far as the propagation of actual results was concerned, each firm working strictly for itself. From a perusal of the technical Press during the last four years, however, it would appear as though some kind of co-operation in research were likely to be introduced in the near future, although it is not clear what form this will take. In Switzerland, from which country we have a great deal to learn on electrical matters, there is also nothing except the laboratories of the Schweizerische Elektrotechnische Verein, where experimental work is often undertaken for the different manufacturers, but only on a comparatively small scale. In England itself we find that in recent years small attempts at co-operation have been made by the laboratories attached to universities and technical institutions, research having been undertaken at the instigation of several of the manufacturing concerns working together. Nevertheless, the latter can hardly be called real co-ordination, and it behoves us to find a better solution of the problem, especially in the entire absence of the extensive laboratories attached to works such as are found in America and Germany.

III. Co-ordination in New Laboratories.

Outline of scheme.—One method of solving the problem would be to erect an entirely new national research laboratory or a series of laboratories to deal with the different branches of science. Such an institution would have to be built entirely at the national expense, as the outlay would be too enormous to be dealt with satisfactorily by any combined efforts of the existing universities and manufacturing concerns. The site for such a research centre would have to be suitably chosen, away from the disturbing electrical influences and the dusty atmosphere usually associated with our towns and cities, although on the other hand it would have to be as near as possible to the industrial centre of gravity of the country. The staff would consist entirely of trained engineers with technical assistance, well-versed not only in research work but also in the requirements of modern engineering practice. The control of the laboratories might be in the hands of a salaried committee appointed by the Government, and consisting of engineers representative of the various universities co-operating and of the different industries interested in the research undertaken. The administrative and financial side could be controlled by other members of the governing committee, selected more for their ordinary business ability than for their engineering capabilities, although the engineering interests would have to be in the majority, as the whole concern would be run as a Government department and would not be worried about making dividends.

The laboratories would take over the whole of the pure research work at present undertaken by universities, colleges, technical institutions, and certain private laboratories, as well as that carried out in the special works laboratories attached to some of our larger manufacturing concerns. No attempt would be made to interfere with the ordinary commercial tests carried out daily in the above-mentioned laboratories, nor yet with the usual routine tests of the students in the laboratories of the training institutions. The subjects for research would be suggested by the manufacturers or the university authorities, who would at the same time be consulted as to what had already been done in that particular line, and who would also be asked to submit proposals as to the best method of carrying out the experiments and as to the results desired. As soon as a research had been brought to a successful conclusion, the results would be communicated to all British manufacturers who had previously declared themselves to be interested in the subject under research and who promised to treat the information as confidential, making use of the same entirely in the interests of national trade. Due precautions would, of course, have to be taken to ensure that the British rights were not in any way infringed by foreign competitors, this being possible through the existing international patent laws.

Impracticability.—The above presents merely an outline of one possible scheme of co-ordinated research, and no attempt has been made to give details of working. Indeed it is not worth while going into the proposal more closely, as it possesses so many inherent disadvantages as to make it impracticable of execution. For example, the cost alone is almost sufficient to condemn the scheme, as there is not only the initial cost of the buildings and equipment but also the expenses of upkeep and salaries to consider. In order to provide buildings worthy of the whole engineering industry of the country and adequate for present and future requirements, many millions of pounds sterling would be required, and such sums are difficult to obtain from Parliament even for an important national work of this nature, although the time for such expenditure was never so propitious as it is at present. In addition there is the important question of choosing a suitable site for the erection of the building. As pointed out, the vicinity of an industrial town is unsuitable, and indeed the large area of land required is almost sufficient to prohibit such a choice. A site would therefore have to be selected out in the country, and then there arises the necessity of providing housing facilities for the staff. Furthermore, there would be great difficulties in staffing an entirely new institution such as the one proposed. At a moderate estimate several hundred fully-qualified university-trained engineers and several more hundred technical assistants would be required, to say nothing of the clerical staff. It would be exceedingly difficult to find this number without taking away from the existing laboratories men engaged in commercial and routine testing, where after the war they will be needed more than ever.

A further disadvantage lies in the practical impossibility of finding a sufficient number of men with the necessary temperament and ability to concentrate their entire attention on research. It has been truly said that inventors are born and not made, men of the Edison type being few and far between. Most of

the great inventions of the world have been developed by men who were in fact only capable of working in one limited direction, and whose fructivity came to an end, as far as new ideas were concerned, the moment they had brought one particular research to an end and perfected one particular idea. In other words, nearly all the improvements and inventions of the past have been the result of the labours of scientists or engineers who, more by chance than anything else, hit upon a new theory or idea, and who continued their ordinary daily routine work as soon as the idea in question had been successfully developed. There are of course exceptions to this rule; but, generally speaking, it is impossible to engage an inventor as such and tell him that for a given remuneration he is to spend eight hours a day devising and perfecting new ideas. Not only would such work be exhausting, but from its very nature the monotony would speedily lead to entire barrenness.

IV. Co-ordination of Existing Laboratories.

General principles.—For the above reasons the whole proposal to erect a new national research laboratory and to employ whole-time inventors may be abandoned as being impracticable. As an alternative scheme, use could be made of the existing laboratories of the country such as are to be found in connection with all our universities, colleges, technical institutions, and most manufacturing concerns. Although perhaps we have still a great deal to learn from foreign countries as regards adequate facilities for research, yet we undoubtedly possess many absolutely first-rate research laboratories where much excellent work has been and is being done. Surely then it is only right that these and their trained staffs should by suitable organization be utilized to form the nucleus of any scheme of national co-ordinated research. This is indeed the basis of the scheme which is now propounded and, as such a scheme appears to offer the only practicable solution of the problem, it is proposed to go into details at some length. It should be pointed out that this scheme has only been put forward after taking into full consideration the actual research facilities and engineering as well as organizing talent at our disposal, not forgetting at the same time our national conservatism or distrust of drastic changes. It is not pretended that the scheme as here outlined represents the only workable arrangement in all its details, there being so many factors to be considered and interests to be consulted that actual details cannot possibly be settled until the general necessity and feasibility of the idea have been accepted. Nevertheless, an attempt will be made to prove that the scheme here put forward not only is feasible but also has special inherent advantages.

Briefly outlined, the scheme consists in centralizing under one board or committee the control of all the research laboratories attached to the universities, colleges, and training institutions of the country, as well as of a large number of similar experimental laboratories connected with private works. Such a board would keep full records of what each individual laboratory was doing, and would receive all inquiries for research work to be done, whether the same came from inside or outside the laboratories in question. Furthermore, the board would keep all published research records of the world and would thus be able to guide individual laboratories in their work. The board would be invested with full powers to order any laboratory to undertake certain research work or to leave another research alone, or indeed to transfer, if considered advisable, part of its equipment and personnel to another laboratory. Finally, all new discoveries would be communicated to the board, which would at its discretion publish the same openly, or else give them or sell them as trade secrets to interested British manufacturers or combines.

Personnel.—In the first place let us consider the central board of control which would have to be set up. This could be composed of private individuals representing the various interested laboratories, manufacturers, and technical societies, or it could consist of a Government Ministry corresponding to the present Department of Scientific and Industrial Research, or of a Government Department similar to the Board of Trade. Owing to the many conflicting interests, and in order to give the whole scheme full legal powers at less trouble and expense, direct Government control is favoured, and it is proposed that the existing Research Department should take over the work. Naturally the Ministry or Board itself would have to be composed of, or at any rate assisted by, experts, among whom engineers would be in the majority, the latter being nominated, say annually, by the universities, the manufacturing organizations, and the larger technical societies such as the Royal Society and the Institutions of Electrical and Mechanical Engineers. Possibly it would be sufficient for the President of the Board alone to be a member of the Government, the ordinary members being not necessarily even Members of Parliament, but being elected to the board purely on account of their scientific, engineering, or business qualifications for the work. It is suggested that the board should consist of about 20 members and that meetings should be held every two months. Naturally, temporary or permanent committees could be formed to deal with special sections of the work, and to these could also be appointed outsiders whose specialized knowledge might be of use. All committees would of course be solely responsible to the board. It is suggested that the seats on the board and committees be honorary except for remuneration for expenses.

The executive of the board would be invested in a whole-time salaried director-in-chief assisted by a number of section directors, who will be discussed later. The director himself would be selected chiefly on his merits as an organizer, because upon him would rest practically the entire responsibility for the successful carrying out of the whole scheme. Naturally he would have to have a first-class knowledge of scientific and engineering achievements and requirements, as well as experience in actual manufacturing work, but his chief qualification would be that of organization and ability to control in the right channel the immense volume of work which would of necessity pass through his department. In view of the great national importance of the whole scheme it is proposed that the remuner

ation of the director-in-chief should not be less than £4,000 per annum.

As assistants to the director-in-chief, but under his control, would be, say, seven section directors, each of whom would take charge of one of the main sections into which the work of the board would be divided. For a commencement the following sections could be instituted, viz. electrical, mechanical, chemical, civil, mining, aeronautical, and agricultural engineering. These seven sections are by no means all that could eventually be dealt with under the proposed scheme, but they represent the main divisions with which a start could be made. Possibly certain sections could be incorporated in others, or, on the other hand, after due investigation, entirely new ones might be deemed to be necessary. In any case each section director would be selected on the grounds of general knowledge, both theoretical and practical, of the branch of engineering in question, his organizing ability being of secondary importance, as the same would be looked after by the director-in-chief. Here again the salary should be in accordance with the national importance of the work, and £2,000 per annum is suggested as being a fair figure to attract the right man.

Each engineering section would be further divided into a number of sub-sections, each dealing with a specialized branch of that particular section. For example, the electrical engineering section could contain separate sub-sections to deal with telephone and telegraph apparatus, generators and motors, switches, medical appliances, insulating materials, electro-chemical processes, measuring instruments, etc. Each of these sub-sections would again be under the control of an expert engineer in the particular branch, all of whom would be responsible to the section director. As salary for these sub-section engineers £1,000 per annum is suggested, although this sum could perhaps be varied to suit the importance and size of the sub-section in question.

In addition to these sub-section engineers there would be employed a number of travelling engineers in each section, who would work parallel to the sub-section engineers under the section director, but who would not necessarily be attached to any particular sub-section. The duty of these travelling engineers would be to visit the various laboratories under the control of the board, to interview private inventors in different parts of the country, and to collect general and detailed reports from all parts upon the progress of research work or the need for the same. For such men a minimum salary of £500 per annum should be paid, as, in addition to being trained engineers, they would have to be quick at grasping new ideas for research, and to have a good eye for determining whether a proposed new idea were worth investigating and developing. In addition they would have to be able to make out concise and accurate reports of the work inspected.

Apart from the administrative and engineering posts, all of which would require really first-class university-trained men, it would of course be necessary to have a supporting staff to assist the various directors and engineers in the preparation of technical specifications and working instructions for the laboratories. As members of such technical staffs younger engineers at salaries of from £200 to £300 could be engaged, such men being selected, say, from the universities direct and being afterwards eligible for the higher posts under the board. The only other personnel demanded under the scheme would be clerical staff to look after the book-keeping, to write letters under the dictation of the engineering staff, and to keep the records of work done by the laboratories.

Executive buildings.—As regards the buildings and equipments necessary for the scheme, it is obvious that all that is required is a central suite of offices for the engineering staff, with rooms for board and committee meetings. The situation of such offices should be as near as possible to the central gravity of the system of laboratories under the control of the board, for which reasons London is hardly to be recommended. London is of course the capital of the country, and the tendency during recent years has been to allocate the main offices of all large business concerns to the capital. At the same time, however, London is by no means the manufacturing or engineering centre of the country, and some city which is better situated geographically should perhaps be chosen. Manchester, Birmingham, Leeds, or Sheffield are all better placed in this respect, and the question of the position of the central offices would also require careful consideration because London has as many disadvantages as advantages.

In any case, whatever city be chosen, there would be no need to erect a new building, at any rate for the commencement. The requirements of the staff would not be anything abnormal, and there are many existing office blocks which could be utilized either with or without alterations. This will be especially the case at the conclusion of the war, when numerous suites will be vacated by temporary war departments. All that would be necessary would be individual offices for the directors and chief engineers, common offices for the assistant and travelling engineers, several small drawing offices, offices for the typing staff, and fireproof storerooms for the files and records. Later on, a new national building could be erected embodying the experience obtained in temporary premises, but, to begin with, this would not be necessary and existing offices could be rented. The cost of the same is difficult to estimate, as it would vary within wide limits depending upon the situation, but approximately £5,000 per annum may be put down for this item.

Records office.—Passing now to the actual connection between the board and the laboratories, it should be stated that this depends to a very large extent upon an efficient system of keeping the records of all research done. Each laboratory would in the first place send in full details as to its equipment and personnel, with exact particulars of the proportion of the same which were available for research purposes. Furthermore, the reports would embrace schedules of the character of the researches being undertaken at the time, with details as to the progress up to date. In the meantime the board would invite the manufacturers, engineering societies, and general public to send in suggestions for further research. All these reports would be care-

fully collected, sorted, and catalogued by the central staff, and resumés entered up on the cards of a card register. It would then be the duty of the engineering staff under the guidance of the director-in-chief, assisted by the sub-directors, to look up and catalogue all published accounts of research and progress on the subjects in question, giving in each case the reference. This cataloguing would naturally involve a great deal of clerical work, but, after all, it is only what each individual experimenter does or should do to-day if he is to succeed. It would mean searching through our numerous valuable libraries for books and publications some of which would otherwise never have been lingered again, as well as making frequent references to the Patent Office. Indeed, it might ultimately be advisable to send engineers to, or appoint engineering correspondents in, foreign cities to collect and translate reports from the libraries there.

This collection of information would in itself involve an enormous amount of work, but the results would be of such immense national value that the time spent would be fully justified. We should finally have an absolute gold-mine of information not only on research matters, but also of scientific and engineering progress throughout the world. It could then be said with truth that British industrial research rested on a thoroughly solid foundation, superior to that of any other country. We should probably discover that in the case of a great deal of present-day research the same ground was already covered many years ago but abandoned as being fruitless. Such overlapping and waste of time could be immediately stopped. On the other hand, there might be unearthed old researches of 30 years ago which at the time had led to nothing but which in the light of present-day knowledge might be pursued further and carried to successful conclusions.

It would of course be impossible to investigate all subjects for research in this thorough manner right at the beginning, and a start would therefore be made with those subjects already being dealt with by the laboratories. As soon as all the available matter on one particular subject had been collected, it would be communicated direct to the laboratory or laboratories which were working thereon or which had expressed an interest therein. The method of communicating such knowledge would vary according to circumstances. If the amount of matter was not too great, a typed report would suffice, or alternatively one of the travelling engineers or the engineer who had been handling the case could go down in person to the university and give a verbal report. On the other hand, if the subject matter were of more general importance, a printed report would be justifiable so that it could be circulated more widely. As soon as the laboratory received a report, it would at once be able in conjunction with the board to decide whether it was worth while continuing the research on the original lines or whether it would be better to branch off in another direction or abandon the experiments altogether. In the very likely event of two or more laboratories working on exactly the same lines the board would have the necessary powers to command the transfer, for the time being, from one laboratory to another of any equipment or personnel. On the other hand, if it should turn out that a particular laboratory was not being usefully employed, the board could order it to take up one of the researches suggested by outsiders, giving at the same time a rough outline of the work to be done and supplying full reports of previous researches, if any, on the same subject.

University laboratories.—From what has been said, it might appear as though the board were to take absolute control of the university laboratories. This is, however, not so at all, as the powers exercised by the board would only be similar to those of the existing Board of Education. The latter controls the work done in the schools and universities of the country, specifying certain methods of working and stating definite results which have to be achieved, without any actual interference in the ownership or management. So it would be with the Board of Research. The various university laboratories would still be used for trading purposes as they are at present, and the ordinary degree or diploma courses would not have to be altered in the slightest. But such laboratories exist not only for routine training work, but also for carrying out absolutely new experimental work, and it is this latter alone which would be affected. The board would work hand in hand with the various boards of management of the universities, and would merely order that specified research work had to be undertaken with certain equipment during a certain time, giving at the same time general instructions as to the carrying out of the research and also supplying all available information on the subject from the central library. The actual details of the experiments, as well as the selection of the personnel to carry out the tests, would as a rule be left to the university authorities.

In the above-outlined control of the board over the university laboratories it has been assumed that the exact powers exercisable would be defined by Act of Parliament. This is, however, not absolutely essential, and the scheme would probably work quite smoothly on a voluntary basis without any special legal powers, provided each party worked in a spirit of give and take, realizing the while that the co-ordination was not only to their mutual advantage but also for the benefit of the nation. On the other hand, cases might arise where the university maintained that the board in its demands was exceeding its rights, or where the university refused to carry out an order which the board after due deliberation considered to be expedient. For these reasons, therefore, it would perhaps be advisable to have the exact relationship between one party and the other defined by Parliament. An Act for this purpose would obviously not need to be of a complicated nature, and would only have to set forth the objects and constitution of the board and state the limits beyond which the board could not order the university to go. If the clauses of the Act were carefully formulated after due consultation of all the parties interested, there ought not to be any difficulty in obtaining parliamentary sanction, especially at the present time.

By this means the individual freedom of the universities would not be hampered at all by the scheme as

far as the ordinary training classes were concerned. Indeed the university authorities in general ought to be only too glad to receive from the board suggestions for research, as at present it is no uncommon occurrence for university professors to be at a loss to find suitable subjects for research for all the students who desire to be put on to such work. Under the proposed scheme, not only would the university authorities be helped in this respect, but also the staff and students would take more interest in their work, knowing that what they were doing was not merely of academic but also of national commercial value. Moreover, the students who succeeded in bringing their particular researches to successful conclusions would afterwards stand a much better chance of obtaining employment with the manufacturing concerns which subsequently took up the ideas involved in the researches. This fact alone would act as an inducement to students to continue their studies for a fourth or fifth year, and indeed would attract to the universities men who would otherwise for financial reasons hesitate before taking up the ordinary university courses. By this means the number of students would be increased, and we should eventually have in this country the same proportion of university-trained men as are to be found in America or Germany.

Student experimenters.—To digress somewhat from the discussion of actual research to the question of the supply of students to carry out such work in the university laboratories, it is interesting to know that just before the outbreak of the war there were only about 5,000 university students in this country, compared with over 10,000 in Germany and approximately 20,000 in America. To-day it is universally acknowledged that much of the trade success of these two countries during the last few decades is to be traced directly to the careful technical training received by all those occupying responsible positions of any kind on the manufacturing or selling staffs. We in this country have by no means been standing still during this time as far as technical education is concerned, but nevertheless we have not made the progress which we might and ought to have done. If, however, we really intend to recapture our lost commercial supremacy after the war, then we must undoubtedly see to it that more of our young men are persuaded to enter the universities, so that our industries may have a continuous and sufficient supply of technically-trained assistants to draw upon.

The reason why we have in the past suffered from a lack of such men was as a rule not to be found in any deficiency in the facilities offered by our training institutions, nor yet in a want of willingness or ability on the part of our boys leaving school, but in the financial incapacity of the parents to allow the boys to continue their technical studies. Thanks to the magnificent system of scholarships prevailing in this country, boys with the necessary ability can now pass right through the universities, even if they are unable to contribute a single penny themselves. At the same time, however, there are thousands of middle-class parents who will not accept this form of charity and who would be prepared nevertheless to send their boys to the universities, even if to do so involved making a family financial sacrifice, provided the boys were more or less sure of obtaining satisfactory self-supporting posts as soon as their studies were completed. Unfortunately, before the war too many of our university-trained men had to begin work as "engineers" at salaries of 25 or 30 shillings per week, which meant that they were absolutely unable to repay anything to their parents for the sacrifices which had been made on their behalf, and indeed in many cases the parents had to continue to assist in their upkeep for several years.

The position of technically-trained men after the war will most certainly be better than it was before, and such starvation salaries as those quoted above will hardly be offered. This fact in itself will tend to attract more boys to enter our universities and colleges, but the inducement would be still greater if the boys, and especially the parents, were sure that in the ordinary course of their studies they would be called upon to carry out commercial research which would bring them in contact with manufacturers and others able to assist them later on to obtain a satisfactory start in their career. This question of the supply of students is by no means an unimportant factor of the proposed system of co-ordination research, because even at present the research in university laboratories relies entirely upon the actual students to do the work, under the supervision of course of the professors and the paid staff. Seeing therefore that the proposed scheme intends to make use of the existing university organizations, it is necessary to make sure not only that the requisite number of students is there now to meet present needs, but also that the supply of students keeps up with the increasing demand as the activities of the research board extend. For the reasons already given, however, there should be no difficulty in procuring the desired number of students to man the laboratories, and indeed the scheme should be welcomed by the university authorities on these grounds alone. Moreover, if the board were made financially strong enough to offer adequate remuneration, it would probably be found that the scheme would attract to the universities for research purposes older men who have ideas worth developing but who have not the necessary facilities or financial means for doing so by themselves.

Works laboratories.—So far the university laboratories alone have been considered, although naturally if the scheme is to be truly national in character the laboratories run by manufacturing concerns must also be included. As has already been pointed out, there are in this country a great number of well-equipped works laboratories, even if the majority are not up to the standard of those found in Germany or America. These laboratories must certainly participate in the scheme of co-ordinated research, because there is perhaps more overlapping and groping in the dark here than in the case of university laboratories. That this is so, and is indeed practically unavoidable under present conditions of working, is clear from the very nature of such laboratories. In the first place they generally attempt too many researches at once and are not properly equipped to do any one of them. Secondly, they are usually in charge of an engineer

whose main business consists in selling as much stuff as possible, and who has therefore not the necessary time to attend to all the numerous details connected with experimental work. Thirdly, it is impossible for each works laboratory to be equipped with a complete technical library to show what has been done on the research in question and to guide the experimenter in his further investigations. Fourthly, each laboratory is intensely jealous of all the others and on no account allows outsiders to catch a glimpse of what is going on, with the obvious result of overlapping, 20 firms perhaps carrying out exactly the same research simultaneously. It is thus obvious that some scheme which will remedy these evils is badly wanted and should indeed be welcomed by the manufacturers.

At the same time such laboratories cannot, owing to the nature of their constitution, be dealt with in exactly the same way as university laboratories. The latter work entirely in the general interest of scientific advancement, whereas the primary duty of the former is to give the shareholders as large a return on their money as possible. Hence the secrecy and jealousy with which the investigations in laboratories are carried on, such a state of affairs being quite natural and indeed perhaps healthy before the war. But under the changed conditions which will prevail afterwards, each individual firm will have to stand by and assist its fellows to the very utmost, not only in manufacturing and selling matters, but also in questions of research. In devising such co-ordination, however, there are certain rights of the individual firms which must be preserved. For example, it cannot be expected that a firm will explain to the board exactly what results have been obtained with respect to investigations which concern that firm's products alone. At the same time there would generally be no harm in stating what subjects were under research, as the board in return would be able to give valuable information as to what had already been done in that line. Similarly the board could not, without seriously interfering with the rights of the individual, order a given firm to carry out certain researches in which the firm had no interest whatsoever, although the board could perhaps recommend that certain investigations were to the firm's own advantage.

It is therefore proposed in the first place that the works laboratories should not be included under any Act of Parliament which it might be necessary to introduce in order to define the precise relationship between the board and the university laboratories. That is to say, there would be no compulsion of the works laboratories to participate in the scheme, although at the same time it is to be hoped that the scheme could be made so attractive that a large number of them would join in, not merely for patriotic reasons, but also because the scheme would offer them material advantages. By carefully drawing up the regulations of the board so as to aim at giving the manufacturing concerns real advantages without prying into actual manufacturing secrets, it should be possible without much difficulty to get over any original animosity.

Assuming that a given firm after carefully considering the pros and cons of the question had definitely decided to put its research laboratory under the control of the board, then the first thing that would have to be done would be to inform the latter of the exact equipment available for research purposes. This information would have to include details as to whether such equipment was free for whole-time research or whether it was partly in use for ordinary manufacturing tests. Furthermore, it would be necessary to state whether any part of the firm's ordinary manufacturing plant could eventually be used for or in connection with experimental work, and if so at what times and for what periods. Also details would have to be added of the staff and workmen accustomed to or capable of superintending or assisting in research work, stating at the same time whether such men were available for whole-time or only part-time work. Finally, data would be required of the class of experimental work which had been, was being, or could be undertaken. It goes without saying, that all this information would be given to the board by the managements of the various works under a strict seal of secrecy, and would primarily be intended for cataloguing purposes in the central library. Should the board subsequently find it advisable to pass the information on to a university laboratory or eventually to another works laboratory, then this would be done without giving any reference whatsoever to the original source. For example, it might be found that several works were all carrying out the same research on exactly identical lines, and as one of the main objects of the scheme is to avoid such overlapping, it would in such a case be more or less necessary to communicate to each one the results obtained by the others. This could, however, with a certain amount of discretion be done without injuring the rights of any party.

Generally speaking, the research done in works laboratories may be divided into two distinct classes, namely, investigations in connection with entirely new principles or materials, and experiments to improve the construction of details of machines or apparatus built in those particular works. Now obviously the latter concerns nobody else but the firm in question, and the latter is at liberty to spend as much time and money as it likes on such experiments. But as to the former research there is an almost unbelievable waste of energy going on at the present day, or at any rate there was before the war, because nearly all the firms manufacturing the same articles were working parallel to each other in their own laboratories behind closed doors. To make this latter point clearer an example may be taken of the numerous transformer manufacturers in this country, who without exception use thick oils for insulation purposes. Although each manufacturer has experimented for years, not a single one is absolutely sure as to the correct physical properties which such an oil ought to possess in order to act simultaneously as an insulator and as a heat conductor. Surely it would be much simpler and better for all parties concerned if such research were carried out absolutely thoroughly in one properly-equipped laboratory only and the results circulated as soon as some definite decision had been reached. Each firm would afterwards be free to purchase its

oil where it wished and would merely have to carry out routine tests to see that deliveries were as near to the ideal as possible, that is to say, were up to the specification. In fact in this respect the whole scheme would act as a great incentive to standardization, which, as is now generally acknowledged, is more than overdue in all our industries. After all, the principle of standardization implies the recognition by the individual of the mean best resultant of separate individual efforts, such resultant being determined by the multitude.

Another example of the need for and the possibility of co-ordination is to be found in the old question of a practical solder for aluminium. All those who have had anything to do with this metal are agreed that such a solder would be an inestimable boon and would revolutionize or at any rate enormously simplify present methods of working with the metal. For this reason, innumerable experimenters in all parts of the world have been trying to solve the problem for years, research being still carried on in private, university, and works laboratories. The greater proportion of these workers is, however, absolutely unacquainted with what has already been done in this field, and is therefore probably following up clues which were thoroughly investigated years ago and given up as hopeless. In all probability a suitable solder will never be found in this fashion, although an enormous amount of the valuable time of countless experts has already been wasted. If, on the other hand, all these experimenters would pool their knowledge for the national good, and if a board of research would then appoint one of perhaps several definite laboratories to take up the research at such points which the combined results of all the other workers showed to be most fruitful, then we might finally solve the problem. This done, the solution would then be transmitted back through the board to all those manufacturers who had searched in vain, to make use of as they thought fit in the interests of the trade of the country.

This question of an aluminium solder is merely given as an example of the advantages of co-ordinated research from the standpoint of the manufacturers' laboratory. The number of problems which could be similarly dealt with is legion. By such action all overlapping would be done away with, the chances of arriving at a satisfactory result within a reasonable time would be enormously increased, whilst the manufacturers' experts would be released to carry out investigations dealing directly with manufacturing problems. Thus, as far as the solder is concerned, the firm's engineers could devote their time to deciding what particular bolted or riveted joints could with advantage be replaced by soldered ones, and also what articles or parts of apparatus could be made of aluminium as a substitute for other metals, to the improvement of the firm's products as a whole.

It will thus be seen that the manufacturer would have in reality nothing to fear from the board as far as his own particular trade secrets were concerned. Even if a particular firm did not at first wish to enter into the scheme on patriotic grounds, time would soon show that the most selfish interests would be more than met by participation. It is true that at first sight the giving up of jealously-guarded experimental results appears to be a loss, but after all it was always a speculation as to whether the research in question would have led to anything definite. On the other hand, a firm under the scheme becomes absolutely assured of being able to participate subsequently in any results achieved by co-ordinated research, not forgetting thereby that by the mere fact of co-ordination the chances of success are vastly increased.

It has been stated that all information imparted by private manufacturing firms to the board would be treated in strict confidence and would not be passed on to unauthorized persons. Around this fact is probably centred the question of adherence or otherwise to the scheme by the manufacturers, because it is only natural that the support of the latter cannot be expected unless this elementary principle be rigidly carried out. As far as the board itself is concerned, this point could be made perfectly clear in the Charter of foundation or indeed in the Act of Parliament pertaining thereto. As regards the actual personnel of the board, however, such absolute secrecy would be more difficult to ensure. For this reason alone it would perhaps be advisable to make the board a direct Government department, so that all employees could be sworn to secrecy, as they are for example in the Customs and Excise Services. At the same time, with a privately constituted board the risk of leakage of information need not act as a deterrent to the scheme, because even amongst private firms there are always to be found a few dishonest employees who are prepared to sell trade secrets to competitors. With a semi-official board of this nature the chances of such persons being employed could by suitable selection be reduced to a minimum.

Remuneration.—One very important point in connection with any scheme of co-ordinated research is a question of recompense for ideas brought to the notice of the board and developed under the auspices thereof. Coupled to this is a problem of the patent rights attached to a new idea which has been successfully developed under the direct supervision of the board. At present each individual experimenter keeps the results of his work strictly to himself until such time as his efforts are crowned with success, whereupon he takes out a patent in order to reap the financial fruits of his labour. This is an important right of the individual and cannot be abolished by a stroke of the pen. If this were done, then the inventors and experimenters, both individually and collectively as manufacturing concerns, would most certainly oppose and keep clear of any scheme of co-operation. Of course on patriotic grounds alone the scheme ought to be supported by the inventors, but at the same time it cannot be expected that these men will sacrifice their present financial rights, however uncertain, merely to enable the manufacturers to pay larger dividends. For this reason some method should be devised by which the advantages of co-ordination may be retained and at the same time the men with inventive brains induced to co-operate.

As far as university laboratories are concerned, the

difficulty is more apparent than real, because with few exceptions the results of research in such institutions have always been openly published in the general interests of scientific advancement. Moreover, such research is as a rule of a general theoretical character and deals with the discovery of new laws of nature without attempting to adapt such laws to the requirements of modern practice. On the other hand, the whole *raison d'être* of works laboratories is to devise the most suitable means of applying the laws discovered by the university laboratories to commercial requirements, for the sole purpose of making money. Seeing, therefore, that the entire organization of works laboratories is based upon a system of financial profit, which indeed acts in most cases as the whole incentive to research, it will be necessary to incorporate some such system in any general scheme of co-ordination.

It is therefore proposed that the individual inventive rights of all workers and assistants under the research board should be fully retained and recognized, so that no suitable person will be forced to stay outside the pale of the board lest he should suffer financial loss. Upon this basis alone will it be found possible to build up a scheme which will be acceptable to the investigator and inventor, who after all form the keystone of the whole scheme of co-ordination. It goes without saying that there are certain difficulties in the way of devising a plan which shall meet with the approval of all interested parties, but such difficulties are by no means insurmountable. By means of a little give and take, especially on the part of the larger and more powerful laboratories, be they attached to universities or works, the plan should be quite feasible. The proposal consists in giving the board of research power to decide in each particular case the actual commercial value of all new ideas developed under its supervision, and to make suitable awards to all those who have in any way contributed to the success of the research. These powers of granting awards could be conferred either by Act of Parliament or by the general consent of the contracting parties, depending upon whether the board itself constituted a Government department or was of a private nature. The fixation of the amount of the awards would be assisted by conferring with the particular manufacturing firms interested in and likely to benefit from the invention in question, although the final decision would rest with the board. Similarly part of the income from which these awards would be made would be derived from the manufacturers themselves, as will be seen later.

Suppose, for the sake of example, that a chemist under the board had been successful in discovering a practical commercial formula for the manufacture of synthetic rubber. The board would in the first place satisfy itself through its experts that the invention was absolutely genuine and fulfilled all that was claimed for it. The rough details of the composition would then be communicated to all firms connected with the board who were likely to be in a position to take up the manufacture, and approximate estimates of the cost of production would be called for. The next step would be to pass on details of what was claimed for the material, along with the cost estimates, to all firms under the board who were likely to be able to make use of the same and at the same time approximate figures of the quantities which could be taken per year would be asked for. Once in possession of the latter the board would be able to decide as to the net commercial value of the invention to the nation and would proceed to reward those who had worked to produce the result, thus applying not only to patentable ideas but also to mere suggestions for improvements. It is not proposed that the directors or chief engineers should participate in any award, except perhaps in exceptional cases, as these persons would be amply remunerated for their services by their salaries. On the other hand, all the engineers and assistants who had actually worked in the laboratories would receive something in proportion to their effective contribution to the final achievement.

In many cases it might happen that a considerable portion of the research had been done beforehand by a firm or individual working alone, and that the board had only been instrumental in putting on the finishing touches. For example, a research under the board might have been begun by merely taking up the threads of some previous experiments as revealed by the researches in the central library. Or, again, the fundamental ideas might have been communicated by some person or firm which had been unable to carry the experiment to a successful conclusion owing to lack of knowledge, time or funds. In such cases no award would under any circumstances be allocated for work done which had subsequently been openly described and the results thereof published to the world before the board took the matter in hand. The award would only be made retrospective for those who had communicated the unfinished results of their experiments to the board for the first time under the latter's seal of secrecy.

The exact nature and amount of the award would be left entirely to the board to decide, each particular case being put forward by the section director assisted possibly by his engineers under whom the research had been carried out. In the case of smaller inventions the director-in-chief in collaboration with the section director might have the power to decide, whilst for minor suggested improvements there would be no need to make any award at all, the ordinary salaries of the staff being sufficient to cover these. In any case the amount of the award would have to be made proportionate to the value of the finished invention to the manufacturers who would afterwards take over the same, and not to the actual amount of work done. That is to say the person or persons involved would have to be treated as if they had been experimenting entirely on their own and had afterwards sold their ideas on the open market, except that allowance would be made for the fact that the equipment and material for the experiment had been provided by the board and that a living salary had been paid for the time spent in experimenting.

For example, it would be of no use offering a £5 note to a man whose idea was admitted by the manufacturers to whom it was submitted to be worth £10,000 per annum. If this were done, the inventors *en masse*

would certainly and rightly fight shy of the board. Payments would have to be made on a scale appropriate to the advantage which not only the particular manufacturers stood to benefit but also which the nation as a whole would derive from the invention. It has been pointed out that in the past too many of the ideas of British inventive genius have been taken abroad owing to their not meeting with adequate financial recognition in their own country. If any scheme of co-ordinated research can prevent a continuance of this circumstance after the war, it will be of inestimable value to the nation and will be worth introducing for these reasons alone. As an adequate scale of remuneration, it is suggested that a royalty of 20 per cent on the net value of each invention to the manufacturers should be paid per year, with an initial gratuity of say 50 per cent of the estimated net value during the first year. By net value is meant the sum or price which the manufacturers would actually be able to put into their pockets as the direct result of the invention in question. This must not be confused with the selling value. Alternatively a lump sum could be paid instead of a royalty, in which case the same could also be computed on the basis of 20 per cent of the net profit.

These figures may at first sight appear excessive, but at the same time they are not really so if compared with the amount earned by commission agents in all branches of trade throughout the world for doing practically nothing. An agent of this nature acts in reality as a mere postman between the producer and the purchaser, and carries practically no responsibility as regards the transaction. As a rule no special education or experience is necessary for the job; a good appearance, a certain amount of tact, and a room to serve as an office form the stock-in-trade. And for his work the commission agent receives 5 per cent, 10 per cent, or even more, of the value of the orders passing through his hands, and often earns thousands of pounds per annum. On the other hand, the experimenter or inventor has usually had some form of technical training, has studied thoroughly the subject in which he is experimenting, works more than the trade-union number of hours per day, and at the end earns a precarious starvation wage. And yet the inventor plays just as important a part, perhaps indeed a more essential one, in the complicated system of modern trade, than does the commission agent. By this it is not intended to imply that the agent is useless and could be abolished, because in many transactions he is indeed an indispensable link in the commercial chain. What is claimed, however, is that the inventor also should receive at least equal financial recognition for his labours, so that without being liable for super-tax he can live in comfort, feeling that his efforts have not been in vain. If this were done inventors would be encouraged to pursue their researches instead of being forced for financial reasons to seek other occupations, so that as a result the total national output of inventions and new ideas would be increased.

For these reasons it is not too much to expect manufacturers to remunerate the inventors to the extent of 20 per cent of the net profits on each particular invention. If the invention consisted of a complete manufactured article, the award could be based on the value of the goods sold instead of on the net profit. In this case the above-mentioned 20 per cent of the net profit would be equivalent to 4 per cent on the value of the sales, assuming a 25 per cent profit. Many inventions, however, would deal only with some specialized part of the manufacture, and the award could thus not be made on the basis of the sales, for which reason it is proposed to take as a general basis the net benefit of profit to the manufacturer. The latter is most certainly harder to calculate and control, but with the majority of English manufacturers there should be no special difficulty in arranging terms to suit each individual case. In this connection it would of course be necessary to give the board powers to check the sales records of the manufacturers through qualified members of the research staff. The sums due from each manufacturer for the various rights purchased from the board could be handed over annually or half-yearly, according to circumstances, and the board itself would undertake the distribution amongst those entitled to receive an award. The book-keeping for this part of the work would have to be carefully done, although at the same time it does not present any special difficulties.

Patents.—Closely connected with the question of remuneration is that of patents, because naturally most of the inventions and improvements worked out under the board's supervision would form subject matter for patents. Hence definite regulations regarding the ownership and disposal of such patent rights would have to be drawn up at the commencement. At present every inventor makes an application for a patent immediately he discovers anything which is patentable and which is likely to bring him money, the object being of course to protect himself against the theft of ideas by another party. This right of the individual must be retained in some form or other if inventors as a class are to be persuaded to work under a board of research.

Under the proposed scheme it is suggested that all patents should be taken out jointly in the names of the particular inventor and of the board of research. The actual preparation of the specification would be left to the trained staff of the board working in conjunction with the inventor, who would be strictly prohibited from taking out a patent in his own name or indirectly in that of a third party. The board would also decide in the first place as to whether an application for a patent was advisable or worth while, and would moreover pay all the expenses connected with the making of a patent application. As soon as the patent had been granted, the board would proceed to dispose of the rights of the same on behalf of the inventor to those manufacturers under the scheme of co-ordination who declared themselves to be interested in that particular line. After the board had pooled the payments from the various manufacturers, the inventor and his assistants would receive their awards in the prescribed proportion as previously outlined. As already mentioned, the directors and supervising engineers under the board would not

participate in any award of this nature as their work would be fully compensated by their ordinary salaries.

In view of the fact that the board had thus indirectly paid the inventor for his patent, it is obvious that the latter would belong to the board and not to the inventor. Nevertheless the inventor should not object to this, seeing that he had received payment for his ideas without any initial worry or expense to himself. Indeed, this fact alone should act as an encouragement to work under the board and to confide patentable ideas to it, because at present each individual inventor has to pay out of his own pocket the not-inconsiderable fees inseparable from the granting of a patent. Moreover, he has to risk that the idea itself will afterwards be found to be unmarketable, and he has in any case to hawk his wares round to the various manufacturers. Under the proposed scheme, however, he has no preliminary expenses and, in addition, he can rest assured that his ideas will be put before those manufacturers who are most likely to be interested in his invention. In other words his invention stands the best chance of bringing in the maximum reward to himself.

It is obvious that, if all the manufacturing concerns in the country were to assist in the proposed scheme, there would be virtually no need for patenting the ideas developed under the board, because each firm would then stand an equal chance of accepting or rejecting the ideas. In case of acception the firm would be informed as to what other firms had taken up the same idea, and thus if considered advisable a working agreement as to output and prices could be arranged. On the other hand, in case of rejection by a particular firm, the latter could not make use of the same idea at any later period owing to its agreement with the board. Hence all parties would be thoroughly protected and there would be no need to take out patents. But it is hardly to be expected that all the firms of the country would participate in such a scheme of co-operation, at any rate not at the commencement, and hence the proposed system of granting patents would be necessary in order to protect those firms, who supported the scheme, from unfair competition from outside.

Another reason for the introduction of protection by patents is to be found in connection with foreign competitors. It is obvious that no foreign firm would scruple to take up an idea merely because this had been developed by and belonged to a British board of research. Hence full use would have to be made of the existing international patent laws, which with all their faults represent one of the fairest means of exchange of trade between nations. It would be of no use setting up a co-ordinated scheme of research in this country if the fruits thereof could afterwards be exploited by manufacturers abroad without let or hindrance. On these grounds alone the proposed board would have to make every possible use of the protection afforded by patents in the way outlined. In this connection it may perhaps be mentioned that this whole question of patents would be enormously simplified by the bringing of our own patent laws more into line with those of America and by the introduction of an Empire patent.

Regarding the disposal of the foreign rights of a patent, the board, as ultimate owner of the parent patent in this country, would have to decide whether it was advisable to allow foreign firms to take up licences in order to compete with the home manufacturers. The advantages and disadvantages would have to be carefully weighed in each particular case, the actual inventor as well as the interested British manufacturers being consulted, although the final decision would rest with the board. Similarly the board would fix the method of payment whether in a lump sum or in the form of a royalty, and would also determine the distribution of the amount received amongst those entitled to receive awards. In order to save expense as well as the time of the staff of the board, it might possibly be advisable to arrange for the disposal of the foreign rights of patents to be looked after by existing patent agents who would be paid the usual commission for their services. By carefully choosing agents who were not only reliable but also thoroughly acquainted with patent matters in their own country, the necessity for the board of employing their own patent agents in foreign countries could be avoided. Of course at the commencement a personal visit of one of the board's home experts would be essential in order to ensure that the firm dealt with was all that it should be, and to make all arrangements, after which visits would only be necessary at intervals provided no irregularities cropped up. In many countries it might also be possible to make use of the services of the same patent agents to keep the central library supplied with up-to-date information on all matters connected with research. For this latter to be done successfully, it would, however, have to be a *sine qua non* that the agents employed were fully-qualified engineers in all branches of science and engineering. If such a firm could not be found, two or more could be employed, each being a specialist in one or more of the branches of engineering.

Finance.—Finally we come to the question of the financing of the proposed scheme of co-ordination, a question about which we engineers are supposed to know nothing, but which in this particular instance is of such great importance that it cannot be overlooked. It goes without saying that a comprehensive national scheme such as the one under consideration cannot be carried through successfully without adequate financial support. At the same time the financial side of the question must not be made paramount to its national importance. As far as possible it is proposed to make the scheme self-supporting, with perhaps the exception of a State grant at the commencement; but even if it be found impossible for the board to pay its way this fact should not be allowed to become a ground for the rejection of the scheme. Rather should the whole idea be looked upon as an absolutely necessary national bulwark erected to protect and assist British manufacturers against better-equipped external competition. For this reason the board should be treated in a similar way to the Boards of Trade and Education, being made as self-supporting as possible,

but any unavoidable deficit being covered by a Parliamentary grant.

As has already been pointed out, the awards for ideas developed under or brought to the notice of the board would be paid for by the manufacturers who took up the ideas in question, so that this part of the scheme would be self-supporting from the beginning. On the other hand, the salaries of the permanent staff, rents of building, general office and travelling expenses, outlay in connection with new researches, special grants to laboratories for work to be undertaken, as well as the expenses of the central library, would have to be borne in some other way. There are three practicable ways of doing this, namely, by an annual state grant, by a system of levies on the universities and manufacturing concerns participating in the scheme, or by a combination of these two methods. It will perhaps be as well to consider each of these alternatives in more detail.

First, as regards financing entirely by the State, at first sight it would appear that this constitutes the simplest and fairest method, in view of the emphasis which has been laid on the national importance of the scheme. At the same time, however, it must not be forgotten that it is really only the engineering section of the community which would benefit directly by co-ordination, and the rest of the country would only receive an indirect benefit, which might indeed be hard to trace to its true source. Now one of the elementary laws of State finance in a democratic country is that national funds should only be devoted to objects which benefit or affect directly the whole community, and hence financing by the State for research purposes is hardly to be recommended. Moreover, a further argument against this method is to be found in the fact that if the scheme were State-financed, then the State would have to have a very large say in the actual control of the affairs of the board. Not only would this latter be objectionable to the manufacturers, but also experience teaches us that it would in all probability lead to mismanagement. It is a curious psychological fact that, generally speaking, as soon as the Government takes over the control of business or private affairs, the last state of such affairs is worse than the first.

Secondly, the advantages of financing solely by the universities and manufacturers would be that the whole scheme could, if desired, be made entirely independent of State control, and that the whole management would then be in the hands of business men, which fact would ensure that the affairs of the board were carried out on purely commercial lines. At the commencement each university would pay an amount proportional to its endowment, its income, or the number of its students, depending upon which of these three bases was deemed to be fairest after careful consideration by all parties concerned. Similarly each manufacturing concern participating could pay a sum in proportion to its capital, or to the amount of the research facilities which it was prepared to place at the disposal of the board. The amounts paid both by the universities and laboratories would vary from year to year according to the total quantity of experimental work done and could not be estimated exactly beforehand.

Under the third proposal, namely, joint financing by the laboratories and the State, the former would merely pay a nominal sum more in the nature of a retaining fee to a consulting engineer, and the bulk of the expense would be made up by a State grant. A variation of this plan would be for the laboratories to pay amounts which would entirely cover the expenses for a lean year in which the work done was at a minimum, and then for the State to step in and cover the balance in those years when the expenditure was in excess of this figure. All these things considered, it would perhaps be better for the laboratories and the State to share the financial responsibilities in some proportion on some basis which would have to be determined later when the scheme was about to be put into operation.

Regarding the exact amounts of money which would have to be found, it is of course difficult to estimate accurately without knowing the exact constitution of the board and the extent to which it would be supported by the manufacturers. Nevertheless, the following figures are given for the sake of discussion, on the assumption that the board would be formed somewhat on the lines previously outlined and also that its work would be roughly as described. Salary of the director-in-chief £4,000, of 7 section directors £14,000, of 35 sub-section engineers £35,000, of 10 travelling engineers £5,000, of 40 office assistants £8,000, and of 10 foreign agents £1,000, making a total of £67,000, or approximately £70,000. Rent of buildings approximately £5,000; stationery and office expenses £2,000. Travelling expenses approximately £3,000. Grants to laboratories for work undertaken approximately £10,000. Special grants to inventors working temporarily under the board £5,000. Total, £95,000 per annum, or approximately £100,000. Of this sum, half could be borne by the State, leaving £50,000 to be taken care of by the universities and manufacturing concerns. Assuming that 20 large firms, 50 small ones, and 10 universities participated in the scheme, then the large firms could each pay an average of £1,000 per annum, whilst the small ones and the universities contributed £500 each.

The above figures, as has been stated, are not to be taken as definite, as they are merely given for purposes of discussion in order to provide some idea of the magnitude of the scheme. At first sight £100,000 per annum may seem to be a large sum, and yet it is nothing compared with our national expenditure during the last four years, it being in fact only about equal to the cost of the war per half-hour. Indeed, the whole expense could be borne without difficulty, in view of the national importance of the scheme. Alternatively, an initial grant of £2,000,000 would provide an annual income of £100,000, and thus put the whole scheme on a permanent and secure financial footing.

V. Conclusion.

In conclusion, the author would once more lay emphasis on the fact that it is not pretended that the scheme as here outlined is complete in all its details

or that the plan proposed is the only suitable one. The chief object in writing this paper was to show that some form of co-ordination in research is necessary, not only from the national point of view, but also in the interests of the individual manufacturers and experimenters. At the same time, the scheme outlined has been gone into fairly closely in order to show that the idea of co-ordination is not merely a utopian one, but that the practical solution of the problem is by no means as difficult as might be supposed on first consideration.

The only other suggestion which the author has to make is that the Institution take the initiative in the matter and invite a conference of all interested parties, in order to settle in the first place the absolute necessity for some such concerted action and to come to some decision as to the general outlines which such a scheme should have. This conference, after one or two meetings, could then appoint a smaller committee to work out the details, which would subsequently be submitted for approval before the plan was definitely put into operation.

Discussion before The Institution, 27 March, 1919.

Dr. W. Rosenhain: This is evidently a paper which has been very fully and carefully thought out, and any such thoughtful contribution to the subject of the development of industrial and scientific research at the present time must necessarily be interesting and welcome. I should like to emphasize that all the more, because I feel obliged to disagree fundamentally with the author in nearly everything he has said, except the one thing that co-ordination of a certain kind, at all events, is desirable. Now why do we need co-ordination? It is obviously a question of economy, economy of effort particularly, because, after all, the thing we are shortest of at the moment is the capacity for effort. It is partly a question of man-power and partly a question of exhaustion in other directions. At the present time we are faced with a double difficulty. We have on the one side the difficulty just referred to, and on the other we have undoubtedly a large amount of leeway to make up with regard to technical and scientific research generally, and particularly with regard to its application and utilization by our industries; and consequently it is very necessary that we should set our house in order and consider any possible schemes by which economies of effort and of money and of material can be effected in attaining the desired result. But we must have real economy, and not false economy. We must not let the desire for organization and super-organization take hold of us too much, otherwise we may sterilize the very plants which we are trying to cultivate by means of hot-house organization, and I think that is what would occur if any such scheme as outlined in the paper were carried out. The point I want to make, which is my fundamental objection to the views set forth by the author, is that research to be fruitful requires freedom, and that freedom is much more essential than the avoidance of even a considerable amount of overlapping. Overlapping in research is not an evil to anything like the extent to which it is in a great many other activities. After all, science and knowledge make their progress in a more or less tentative way. Men discover ideas, they discover facts, or what they believe to be facts, they publish them, describe them, and then they are tested by discussion, by controversy—sometimes very sharply tested by controversy—and ultimately, gradually, the truth is evolved in that way. It is not possible for any board of men, however competent, however highly paid, sitting in an office whether in Whitehall, or Sheffield, or Birmingham, to decide when the truth has been discovered by a set of investigators. That kind of organization is hopeless, and if it were attempted to carry it out it would simply sterilize the whole business. There are other difficulties. The scheme would be sterile because it would not attract the right men. If research were regulated and co-ordinated in the way suggested, a great many men would seek freedom for their activities in other directions—men who are valuable and most urgently needed in these lines of activity. Then it would limit the scope of individual genius; and the advancement of science particularly, and the advancement of invention, are very much matters of individual genius, and the individual genius must be given plenty of scope: he would not brook control. A good many of those present have probably felt the advantages and disadvantages of control during the last few years, and I do not think we want to see it extended in this methodical manner over our research laboratories. Finally, an organization of this kind would be very apt to entrust important work to the wrong man, or the wrong laboratory. Of course, mistakes would occur in any case, but the difficulty is to foresee which laboratory or which man is the right one for a given problem. It must largely be left to the initiative of the individual, and he will find out for himself, or circumstances will very soon show him, whether he is the right man or not for dealing with that particular matter. I should like, in conclusion, to submit one or two constructive ideas of an alternative kind. Economy of effort in scientific research can be realized by the encouragement and development of existing laboratories rather than by setting up a large number of new laboratories by new organizations all over the country. The reason, again, is the shortage of the right kind of men to staff those new laboratories. We have a number of institutions, universities, colleges and other places, which have shown very well that they can do research, and do it extremely well; and the first step in economy I would suggest is that those institutions should be very much more fully utilized and supported, both financially and morally and in every possible way, than they have been in the past. That, for the moment, is certainly the most economical line of advance. As regards works laboratories, that is a more difficult matter, and there the collaboration, the co-operation of groups of firms having similar interests, is the only method of attaining

economy. I should like to say a few words regarding the author's reference to the possibility of a large central laboratory. I think he has not realized to what an extent—although it is still an inadequate extent—such a central research laboratory is actually in existence. The numbers of the staff which he suggests are not so very much greater than the existing staff of the National Physical Laboratory. They are not, of course, what he calls "whole-time inventors," but we have a nucleus there. I do not want to suggest that it should be developed into a single, universal central laboratory; that is entirely impracticable in my opinion, but it is one of the places which I personally should like to see immensely developed. Then as regards co-ordination there is a great possibility; and I think a great deal is being done in the best possible way by just such bodies as this Institution in the discussion of papers and the work of research committees. All those are activities which do a great deal towards what I should be inclined to call loose co-ordination, which is the only kind that can be profitably used in this way. There is one thing which I think could be developed a good deal further than it has been, not only by this Institution but by united technical and scientific institutions all over the country, and that is, we want something in the nature of a clearing-house, or an information bureau, a body or an organization to whom it is possible to refer for information, for references, and for elementary facts. There ought to be some special body or organization to answer questions and give scientific information; and if that information were readily available a great many more people would avail themselves of it, and work would be better done and better utilized.

Mr. C. F. Proctor: I feel, unlike the last speaker, that there is the nucleus of a very good idea in this paper. I quite agree with the author's remark that we must wake up, but I doubt whether the war has done much more than rouse up a few who will only sleep the sounder afterwards. I cannot conceive anything that will really arouse the average Englishman. I quite agree with the author's remarks about the foreigner at the top of page 135, col. 2. He will take up an idea very much more readily than we will. At the top of the second column on page 138 the author says: "The board would be invested with full powers" to say what a laboratory must take up and what it must not do. It seems to me that is too drastic; there would be no end of opposition; and though I say I think the idea is good, I think it might be a little modified so as to make it a little more palatable to the existing laboratories. On the same page, it is stated that the board should be nominated annually. That may be all right, but if they are nominated annually they should hold the post for two years, otherwise we shall have this position: the moment the thing is started everybody is elected, and at the end of the year everybody is cleared out, and the new members will know nothing about what is going on. If some of them hold the post for two years, those remaining in office will be able to inform the new members as to what is going on. On page 139, the author says that the whole success of the scheme depends upon the ability of the staff to grasp at every idea that might be turned into something of value. That, I feel, is very important. We have seen, unfortunately, in this war that many things of value have been brought forward, and some have been adopted and some have been shelved or only adopted after a great deal of pressure. If we are going to have a board like this we must have men who are sufficiently alive to take up new ideas. I quite agree that if there is going to be such a laboratory it should be in the Midlands rather than in London. I may be prejudiced, but I think London is a sort of white elephant, too big to be handled. In the middle of col. 1, page 140, I most strongly support the author's remark that old ideas which have been investigated and laid on one side as impracticable, must not be left on one side but taken up again. There especially comes to my mind Swan's lamp. He laid it aside because he could not get a sufficiently good vacuum, but when Crookes brought out the radiometer Swan communicated with him and succeeded in making a first-class vacuum. On page 142 it is suggested that there should be only one laboratory. I say emphatically, No! We must have at least two. Probably most of the older members of this Institution remember Edison's patent of a tar-paste filament. A number of thoroughly able men said it was quite impossible to make such a filament, whereas at least as many others said it was possible and only needed elbow-grease plus ordinary knowledge to make it a success. That is also true of a great many other things. I am glad to see on page 147 that the author believes that our colleges are run by business men. Some people might doubt it. But if such a thing as this is to be a success it is essential to have business men there, and I think the essence of the thing may be found in what I would call the idea of trying to make it pay. Let those employed feel that their duty is to make the idea workable, if possible, and when it becomes a success pay both them and the firms (as the author suggests) well. Some time ago I was on a Committee which brought forward the question of research, before this Institution. I was in association with Mr. McLellan and Mr. Merz, and we backed very strongly the idea of institutions supporting a laboratory that was to work out ideas for firms. The man employed at the work was to have full credit for the discovery if he made one, but the firms who were contributing to the cost were to have the power to say the thing must be kept private for so many years at the discretion of the institution; but when published, as it would be later on, the man employed who made the discovery was to have full credit for it, and he was to be well paid. The institution was to be paid a certain sum all the time the matter was being kept private, to refund them for the work that they had done in connection with it and the support they had given to the idea. During the war the Inventions Laboratory was formed. If an inventor can go to a board like this with his idea, give it to them, they work it out, and he gets a fair payment for his idea. Then we might expect improvements to go ahead, but the present arrangement is for a man to patent his idea (that is publication) and the big firms, if they find it is worth having, then take it and ignore the inventor. If we can make an idea of

this kind work I do not say quite so drastically, but the essence is right we shall help the country enormously.

Mr. L. Gaster: The problems raised in this paper are of special importance to the coming generation, and to the young men of to-day. The educational opportunities offered to young men entering upon a technical career are already far greater than in the past, and in the future education can no longer be regarded as "a rich man's hobby." Besides educational facilities, however, it is vital that there should be such prospects as will encourage young men to undergo this training. A man devoting his life to research, either at private works or State-aided industrial associations, not only should receive an adequate salary but should participate in the rewards for any valuable invention he may make. No doubt it may be desirable for the firm or association for which he is working to make an agreement with him, according to which they have the first offer of such inventions on mutually agreeable terms; but in the event of their not taking it up the inventor should be free to develop it himself. While the scheme proposed by the author is obviously difficult to realize in its entirety, it contains some valuable elements. We must all agree that efforts should be made to prevent overlapping of work, but to a great extent this could be done by co-operation between the leading centres on a voluntary basis. In visiting several of the chief provincial universities some years ago I was much impressed by the valuable work undertaken, and the extent to which co-operation is already carried. It should be borne in mind that such universities only derive a part of their revenue from the State, and could not therefore be compelled, even by the Board of Education, to adopt or abandon certain researches as the board thought fit. Similarly in regard to the publication and indexing of results of researches, it is difficult to imagine a compulsory scheme being applied, and it would seem desirable that some method should be adopted, unifying so far as possible the various efforts to record experimental work that already exist. In the United States reports of work from various research laboratories are presented monthly in the *Journal of the Franklin Institute*. In this country there does not seem to be at present any similar avenue for the publication of data issued by industrial laboratories. So far as patents are concerned, an investigator could obtain all the information he needs at the Patent Office if the work of the latter were somewhat amplified. As the staff of the Patent Office is mainly scientific and technical, and it possesses already a good library, it is possible that a central bureau might be established in connection therewith, working in co-operation with the chief scientific and technical institutions, where researches of value might be tabulated in the manner suggested. I would venture to suggest that by an extension of its duties the Patent Office could, on payment of a suitable fee, supply an inquirer with a record of published data bearing on the problem in which he is interested, before he proceeded to the further stage of applying for a patent or even before he decided to commence his investigations. In this way much needless expenditure of money and effort might be saved.

Mr. W. Judd: The proposal made by the author is, I think, a natural one, and one which will have to be adopted in some shape or form in the matter of co-ordination; the central body will naturally obtain information from all the existing laboratories, and, without introducing any drastic form of discipline or of control, it would have a very great influence upon the work that would be carried out there. What I imagine would be the initial difficulty would be that most of the laboratories are inefficiently equipped owing to lack of funds, and I should imagine that almost the first duty of the central body would be to contribute such funds as were necessary to place the laboratories of the universities and technical colleges in a position to carry out continuous research work. That, I think, is the more probable line of success. Then with regard to the advice to be given to works laboratories, it would be exceedingly difficult to tell this firm or that association of firms that they are to carry out any specific research. But again, recommendations and wise suggestions to them would probably result in what might be called a quasi-co-ordination; and, as regards the industrial laboratories, it seems to me that it would be most desirable that any associations of firms or industrial bodies who have decided to undertake researches should associate themselves with the scientific institutions which exist for the furtherance of that same industry or art. For instance, in all matters of electrical research this Institution should be associated with them; in matters of mechanical engineering as apart from electrical, one could quite justly say that the Institution of Mechanical Engineers should be associated with the industry in the same way; and so on. This would secure that the scientific view should be well mixed, so to speak, with the industrial, in order to obtain a greater measure of success. The scientific institutions themselves would also form a very valuable link between the industrial laboratories and those of the universities.

Mr G. H. Ayres: We have had a number of papers on research work, but, before we can hope to get very far in the co-ordination of research in the works and laboratories, the first thing to consider is the psychological problem of reconciling the conflict which exists between the highly technical type of mind and the type of mind engaged on works management which one might call the "production first" type. Both types of mind will be readily appreciated by those who have had even a small amount of designing experience. It seems impossible, to my mind, to reconcile these two types under one roof. The university type of mind is decidedly suitable for purely scientific research. For industrial research the type of mind required is essentially inventive, essentially practical, with broad experience, a keen sense of proportion, observation and foresight predominating. In the university type the mind is often too theoretical, stereotyped, and quite disproportionate. The next thing one would suggest is the centralizing of laboratories in certain districts, because if the geographical position of various industries throughout the kingdom were analysed, one would come to the conclusion that there is, to a greater or less extent, a distinct localization of each type of industry. For instance, in the cast iron piping industry two thirds of the king-

dom's output is confined to one straight line 40 miles long, from Chesterfield to Melton Mowbray. I think, therefore, that a scheme in which laboratories are situated fairly centrally in relation to the industry concerned would be a very good plan, and has sufficient in it to warrant the Institution inviting a paper and discussion on it. I should like to mention one other item. The author suggests that university students should be permitted to do research work of an industrial nature. One feels inclined to doubt whether such a step would meet the requirements of manufacturers; because, if educational training and industrial research are combined, since the educational training demands more or less a sandwich sort of system, the continuity of the research work is lost. Another point to be taken into consideration is how many of our universities are already sufficiently equipped, and have space available for extensions, to carry out industrial research on anything like an adequate scale. The same, of course, applies to those municipalities who have research laboratories. For instance, a short time ago I had in hand some aeronautical work, and in a routine test where the dimensions of the article to be tested were by no means extraordinary, it was found that the university had no machine capable of performing that test. Another drawback is found in practice, in that many of our research staffs and university students and authorities are not permitted to participate in the discussions at a meeting of an Institution such as this; and I certainly think it is time that such restrictions were removed. It would certainly be to the advantage of the country; for surely men of such a calibre would have sufficient discretion to know when they are divulging secret information and when they are giving information of national scientific value without divulging secrets. I will mention one further point. The author deals with the various individuals to be put on the board, and he puts down £4,000 for the director and about £2,000 for each of the section directors. He then gives a figure of £500 for travelling engineers, and says that these travelling engineers should have a sense of proportion and know when a particular scheme or invention is going to be of practical use, and whether to recommend or reject it. It seems to me that he is here giving rather considerable power to the travelling engineer, incidentally relieving his superiors of responsibility, and it seems contradictory to his statement in the third paragraph on page 135, col. 1. Thus, if we are going to permit one man to accept or reject, the proposal seems to be defeating its own object.

Lieut.-Colonel A. G. T. Cusins: The author evidently recognizes that trade competition is a state of war; but I doubt whether he realized the extent to which we had been at war with foreign nations, and more particularly Germany, for the last 32 years to my knowledge. It is perfectly obvious that some co-ordination of all the research work that is going on will have to be undertaken if we are to get up to date in engineering and scientific matters generally. Co-operation is comparatively easy with a few organizations, say anything up to a dozen, but when we get to the larger numbers which would be involved, it is hard to see how it is to be carried out without some central bureau of information. I do not like the word "control"; centralization is apt to lead to pedantry; but what all of us require is immediate access to information. In that connection we must all agree with the author when he refers to the necessity of a very good library. Under the heading of "Records Office," he says that all the reports from outside to the centre "will be carefully collected, sorted, and catalogued by the central staff, and résumés entered up on the cards of a card register." To get out all that information in a form which may be easily digested is, I think, the crux of the whole matter. How it is to be done is the problem. It will have to be worked out in very great detail, and with very great care; but at the present moment it is difficult to obtain immediate information. One can write to various bodies and get it, more or less, but there is no central authority to which one can write and get an immediate reply Then as regards the encouragement of research, many ideas are lost for want of funds to carry them out. There should be, in connection with research, some body to which a promising inventor could refer his ideas, and if they were approved by such a body then there should be some funds for putting them into practical form. In connection with universities particularly, some form of scholarship, which should take the form not so much of a prize as the granting of special facilities, is well worth considering. In conclusion, all those concerned in research ought to hold their heads up and insist on being heard, if possible. The people who create are the people who will control future development, and unless the creative brain is considered we may find ourselves outpaced by some nation which will not only consider their own creative brains, but will take advantage of ours as well.

Mr. J. G. Pearce: The paper is a bold and courageous attempt to deal with co-ordination in a field in which co-ordination is admittedly difficult. In parts it would appear that the author did not fully realize the great changes that are taking place in British industries in the direction of amalgamation, or appreciate the existing scheme of the Research Department for encouraging the formation of research associations, since he speaks of the manufacturer who is "still content to jog along on his own, too independent or too proud to seek the help of his fellow-workers." If manufacturers have not shown any undue haste to form such associations, it is mainly because they fear that the powers retained by the department will sap their independence of action, although these are only a pale shadow of the powers that the author would confer. He suggests that a huge national laboratory would be impracticable on account of the difficulties of cost, staff and site. I would suggest that the real ground for impracticability does not lie in any of those things, but in the fact that concentration beyond a certain point defeats its own ends. I think it may be taken as axiomatic that in this country progress comes through local administration and responsibility, co-ordinated by central supervision. This gives play to the emulation which arises from local rivalries and municipal rivalries, and finds for a maxi-

mum number of people some function of interest to be performed with a minimum of bureaucratic officials. The suggestion that a Ministry of Research should take control of research institutions cannot be taken seriously, because it would ignore those fundamental considerations on which our whole system of government is based, our genius for decentralization and devolution, independent responsibility and local action. The drastic character of the proposals is somewhat modified by the suggestion that the Board should have the same relationship to the laboratories as the Board of Education bears to grant-aided schools, but it must be borne in mind that part of the money used for financing research would be privately subscribed. It is proposed to set up a central organization having 63 officials and 40 office assistants, none of them active research men or inspirers of research men, taking out of a total maintenance cost of £97,000 per annum, which includes office accommodation, stationery and travelling expenses, a sum of not less than £67,000. How much is left for endowing research? In any case the scheme, which is designed for and is ambitious enough to cover the whole country, and yet involves the expenditure of no more than the sum of £97,000 a year, will not scratch the surface of this vast problem. These points are so fundamental that any other remarks must refer to matters of detail. As Dr. Rosenhain has pointed out, it is impossible to organize pure scientific research. Interference with or pressure on a research specialist does no good and may do harm. Such work can be, and of course ought to be, encouraged with sympathy and material assistance such as the Department of Scientific and Industrial Research is affording. More scholarships for youths from the secondary schools to the universities are required, and financial assistance must be given to mature workers. The universities themselves are already sufficiently independent in spirit and some are sufficiently well endowed, to be able to refuse, and rightly refuse, to barter their independence for the sake of a co-ordination of effort of doubtful value. They know that the personal factor enters so largely into pure research work as to make co-ordination difficult and even barren. In one place the author suggests that legal powers are necessary, and in another that they are not; in one place that the Board should control works laboratories, and in another place that manufacturers should have the option of entering the scheme. Such dragooning as compelling a privately-owned laboratory to become part of a vast State scheme is indefensible. I would suggest that the primary error lies in the supposition that to secure the advantages of co-ordination a geographical centralization of control is desirable, while still less right is the assumption that co-ordination involves the loss of all local independence and power of voluntary action. If co-ordination did involve these things it would be purchased at too high a price. From that point of view the principal thesis of the paper would appear to be wrong, and the problem of what should be done is not so easy as it would appear on the surface. It does not admit of a simple solution, and there I should like to indicate exactly where I agree with Dr. Rosenhain and where I differ from him. Pure science research, as he says, does not require co-ordination in the ordinary sense. It is a positive advantage to have a number of men working at the same problem, looking at it each from his own angle. But in order to minimize duplication and overlapping a world-wide collection and dissemination of information concerning published researches is required, and in that respect I can cordially agree with the author with regard to the records office, which should be attached to each works and university laboratory. One might examine in detail the suggestion put forward for a bureau of information. In my view every institution which requires to be supplied with information, whether it be a manufacturers' association, a technical institution, a research association, or a works laboratory, or whatever it may be, should have attached to it a department known as the intelligence department, to serve as the records office for filing information and for systematically obtaining it. It should be in touch with sources of information, and I can conceive that the common interests of such departments of intelligence might lead to the formation of a central bureau, which is very closely linked up with the proposals for a united societies' library; but I do not think that a central bureau which merely records the bibliographical entries of additions to existing knowledge, such as has been established in Paris or Brussels, would be of any particular value unless it were the apex of this pyramid of local research departments, through which the central body would function, and I would suggest that it is because the central bodies in Brussels and Paris have not been supported by local institutions that they have not justified the expectations of their founders. I differ from Dr. Rosenhain as to the impracticability of co-ordinating industrial research. The problem of co-ordination will here solve itself owing to the high cost of such work when undertaken individually. The high cost of industrial research makes the formation of research associations imperative. That is one solution, and centralized laboratories for groups of works represent another equally as interesting. Interchange of information, and interchange of visits between the staffs of industrial concerns present another. The ready adoption by industry of the results of pure science work is largely a matter of having men associated with industrial firms who can carry on industrial research. In supposing that manufacturers will convey all the results achieved to a board of control, even under the strictest secrecy, I think the author betrays undue optimism. The Department of Scientific and Industrial Research has tried that and found it wanting. Exactly how industrial research should be co-ordinated is an extremely difficult matter, into which time does not permit one to enter; but it is much more complex than the paper would lead one to anticipate.

Mr. C. C. Paterson: I am sorry to say that I am in accord with a good many of the speakers this evening in disagreeing with the author of this paper in very nearly every particular. This paper seems to me to propose nothing more or less than the introduction of militarism into research. By that I mean it is taking away all the human element, the incentive which comes from the personal satisfaction of any man in controlling to some extent his own destinies. Now before we

undertake such a big change as this we must have thorough justification for it. The author has pointed out in the paper that neither America nor Germany has co-ordinated its research to any appreciable extent. We have therefore no actual experience to show how such a centralized organization as this will work out, or whether it is in any way necessary. The author gives two main reasons, as far as I can understand it, to justify this large, all embracing scheme. The first one is organization. He finds a wonderful panacea in organization. At one point the author triumphantly sums up the whole thing in the words "Unity is Strength." I suggest that in a matter of this kind the curve connecting unity and strength has an optimum value, and that optimum value lies fairly far down on the scale of unity; that too great an attempt at unification is going to mean great weakness. This is certainly indicated by what the author says on page 139. He suggests that he would have a number of large departments under separate directions—mining, civil, electrical and so on—different sections, not necessarily located together. Now my notion of an ideal laboratory where research can be carried out with the greatest prospect of success is a small unit, complete in itself, where different branches of science can combine in close co-operation with each other. I am sure one would never get good electrical research by divorcing it from the best physical or chemical influences. One must have a laboratory which contains all the sections. Then the second main reason the author gives for his proposals is the avoidance of overlapping. One of the greatest disadvantages, in my view, of his proposed scheme is that it is designed to prevent overlapping. As Dr. Rosenhain has already pointed out, overlapping in research is most vital, and to try to avoid overlapping is a fallacious policy. It would be easy to run through the paper and make remarks in detail about many portions of it with which one disagrees. I should only like to take exception to one or two points here in detail. First of all, where the author says that in Germany the firms have sunk their individuality and combined for patriotic reasons, I cannot believe that these firms did anything of the kind; I should think they were bought up by the larger firms. Then I take a very strong exception to a remark on page 144, where the author says: "On the other hand, the whole *raison d'être* of works laboratories is to devise the most suitable means of applying the laws discovered by the university laboratories to commercial requirements, for the sole purpose of making money." I think that is taking an exceedingly low view of any research or of the running of any industry. I hold that industries are not carried on for the sole purpose of making money. If we had alone that low ideal in our industries they would never prosper. I am sure most people in this Institution work mainly with the idea of building up a strong industry in this country, and that as far as they are concerned the actual making of money, though necessary for stability and future progress, is not the only consideration. For dealing with research in this country I prefer the idea Mr. Judd has put forward, in preference to that of the author. Let us have a number of strong units; let the existing university and other laboratories be really stiffened, as regards both staff and equipment; let us have a number of units which are really efficient each in itself, to cover a good range of subjects, and try to get co-ordination between them through the mutual intercourse of their members. It appears to me that in this way we shall do far better than by adopting a big central scheme with its apostolic succession of director and sub-directors and with the deadening influence of a Government Department at the head of it.

Mr. E. T. Williams: I take a rather different view from that of the speakers to-night. My opinion is that in this paper we have proposals of great value. We may not agree with the details, but in the spirit of it we have, I think, something which we should take up and carry through. Now what I think the author felt was this. We have in our Empire many most admirable scholastic institutions and research laboratories, which are not co-ordinated and, what is even more important, there is no organization whereby the potential value of all the brain power employed in them can be utilized in industry. The author saw, when living abroad, that the Germans excelled in breadth of vision and in organization; and we have to face the fact that the United States are not only approaching a similar excellence in organization, but that they have what the Germans lack as a people, viz. creative power. Our Empire has to face the important fact that the United States with their wonderful national resources, creative power, and organizing ability are going to be very keen competitors. I believe we can meet them if we follow the spirit, though not necessarily the letter, of a paper like this. Those of us who have lived in the East realize that the future line of demarcation between the races, as regards progress, will be that those who use their brains are going to lead. The Eastern races particularly are such admirable workers with their hands that as they are developed they will very rapidly approach in excellence what we have attained ourselves; and, if we are going to hold the same comparative position in the future, we have to look to brains. It is by means of co-ordinating the possibilities of our brains that we shall utilize them to the best advantage. I should therefore like to illustrate on the blackboard by a diagram a very simple way of carrying out some such scheme as this. Suppose we have a board as proposed by the author, then I think that that board should consist of two elements, one of which I will call research and development, and the other I will call application. There is any amount of development and research work going on to-day which is never applied. The board I should keep as small as possible; and I do not think, anyhow to start with, that it ought to undertake research work itself. The work of the board should be to co-ordinate research, not to do it. This would be a paid board, which should set up in the country honorary committees. The country can be very simply divided up in this way; and we ought to be very careful to secure in the committees the valuable elements of both research and application. But in a district, say, like Manchester, where there are several very important industries, I would have sub-committees of these honorary committees dealing with the industries themselves. So here we have an industry, say, dealing

with cotton, looking out for development in cotton work but co-ordinated through the committee with other industrial development. I think the value of this organization would be very great. First of all it would be comparatively small, and inexpensive to run as the board would not be carrying out development itself but would be co-ordinating all the efforts of the committees in the country, and in that way making the greatest use of them. A man having an idea to-day knows nowhere he can go and get protection and development for it. He would be able, under the proposed scheme, to go to such a board as this, and the board would know the way and the place to get that man's idea developed.

Mr. L. W. Phillips: The main fact which has been borne in upon me both by the reading of the paper and by the discussion which has taken place since, is that the success of any attempt at the co-ordination of research work depends not so much upon the organization as upon the spirit which the scientific workers bring to bear upon their work. The issue of whether co-ordination is to be successful or not is far wider than the limits of this Institution. We are considering the whole problem of individualism versus collectivism, and the one thing that stands in the way of any progress which we might make is the fact that we are mainly dealing with individualists. Take, for instance, the individual difficulty. It is often assumed that when an engineer gets into a position of responsibility he must never "give himself away." He is often looked upon as an individual who is an expert on all subjects and possessed of all knowledge, so that it means quite a lowering of dignity and loss of pride on his part to have to confess that there are many things he does not know. Sincerity under these conditions is not easy, but until we confess that there are a few things which we do know and many that we do not, we shall not make any progress. Supposing, however, we are able to subdue the individual interest for the collective welfare of one branch of our industry, what then? The author has pointed out on page 142 two very clear examples: the failure to learn anything definite about transformer oil, as to its combined insulating and thermal properties, also the question of aluminium rubber. Why is that so? Is it not because individual firms are concerned not so much with the production of efficient apparatus or the best materials, as with their exploitation of that product and the extraction of patent and royalty rights from it? Going further, however, and assuming we get the co-ordination so far as the whole electrical industry is concerned, what is going to happen when we come to conflicting industries? Take the gas and electrical industries. There has never been any fair basis of comparison, no one really definitely knows the limitations and possible adaptations of gas and electricity, but if we are going to tackle research in a national spirit it may mean that some industries will have to be limited or even eliminated in the interests of the whole. Still further, I should like here to make a plea for the internationalization of science. It is the author points out on page 141, the whole object of the specialization and co-ordination of our industrial research is simply to sharpen our weapons that we may be foremost in the fight for the markets of the world, for the making of ourselves supreme, then it can only mean that the whole of our efforts are going to be frustrated and overthrown by another world conflict. For it is generally recognized that international warfare on the battlefield is only the continuation of industrial warfare. I would plead that we internationalize knowledge; that in a scientific association like this we endeavour to get that spirit into our investigations which shall make it come about that the desire of research shall not be national supremacy, but the welfare of the whole of humanity, and that our research shall be carried out in such a spirit that we can be sure the world will not be overwhelmed by such a disaster as we have just passed through. In our technical abstracts from the foreign Press we are willing to take advantage of the work of foreign scientists, why then should not we follow the lead of Labour? Labour is setting up its "Internationale" to regulate industrial conditions throughout the world, and we as scientists should follow that lead. We should have an "Internationale" of Science where, so far as possible, all can put forward their ideas not for the profit of one nation but for the well-being of the whole world. There is one point which I think is very important and that is the establishment of a central library. It would help very largely at the present time in scientific research and make more effective that central library when established, if we had a standard classification. When one reads a scientific article one has either to go very carefully into it to know exactly what it is dealing with, and then perhaps find that it is not the particular subject in which one is vitally interested, or else classification has to be performed carelessly or left to people who are not technical and who in consequence cannot do it well. If we could persuade our Engineering Institutions to standardize classification so that at the head of every technical article which appeared in the Press there were some specified letters showing what the article referred to, then it would save a great deal of time, and allow of indexing being carried on by non-technical people. Then, too, it would be a great advantage in the existing libraries. A man may have the run of one library, know exactly where to put his finger on technical details, but goes to another library and has no chance of finding what he wants. With a standardization of classification applied to scientific literature throughout the United Kingdom to begin with, it would make it possible to get at a good deal of scientific information which at the present time is not available. In this connection I would point out that in *System* for last October there was the beginning of a mnemonic method of classification, taken down to the second letter. That is a scheme which I believe would recommend itself very largely to engineers, for at the present day the system which holds the field is that of Dewey, which is a decimal system having relation to the subject. A number-classification can never be suggestive of the matter dealt with. Dealing with the utility of the mnemonic system I would point out that the British Industries Fairs have adopted it and the American Navy, in classifying 20 000 documents of experience gained during the war, have also adopted the mnemonic

idea. One final suggestion I should like to make is that the Institution should send round a form in which they invite research workers in this country to send in their names and the particular research with which they are associated. The Institution could then group individuals that are connected with each particular line of research, and just as we have our local Institution meetings it might be possible, even in a district like London, to have people who are interested in one particular line of research meeting together for their mutual advantage.

Mr. G. L. Addenbrooke: I have had a good deal of experience of what people are pleased to term research work, and I should like to make two or three suggestions. There is a very great value in the publication known as *Science Abstracts*; but the difficulty which I have found is that the abstracts are not long enough; in fact my feeling for some time has been that it would really be almost better to cut the abstracts down to the mere titles and practically do away with the descriptive part. The abstracts at present in the department I have come across are often very misleading. I do not blame the abstractors; they are limited to a certain space. If one has only a short abstract of a paper one gets very often a misleading idea of what is in that paper. I believe the value of *Science Abstracts* would be enormously increased if the abstracts could be somewhat longer, and all figures and tables possible be put into them. I do not think that would increase the expense very largely. There is another point which has come before me for a great many years, and that is what may be called the starvation of the scientific societies of this country. I have presented papers on several occasions to such societies, and some of them have been published, and I have had opportunities of talking to the secretaries, and I myself have been secretary and treasurer to one of those societies. The bane of all these societies is the cost of the publication of journals in comparison with their resources. It does not apply to a large Institution like this, which has sufficient resources to be able to publish a great deal of matter, but a number of societies such as the Physical Society could not possibly do so. The incomes of many societies in this country have not advanced during the last 20 years anything like proportionately with the number of research workers, and research has been stunted very largely in consequence. The censors are under the compulsion to cut down every paper to a minimum and often to reject papers they would pass if they had more liberty. Every notification one gets from a secretary is: "Be as brief as possible; cut it down," and the censors very often cut out paragraphs which they think are unimportant, but which probably other people might think very important indeed. Well, I think that is a great pity, and one which might be remedied at a very moderate cost. A few hundreds a year given to leading societies who are not wealthy, and societies like the Physical Society who are very poor in comparison with the importance of the work they have to do, to allow them to extend reasonably their publications would give a chance to a great number of original workers working by themselves, and I believe that is the basis on which to found any efforts to foster the best research. I have for my own work gone over a good deal of the work of Maxwell and Joule. One of the reasons why Maxwell and Joule did such a very great work was that they had moderate private fortunes. They did the work for the love of the thing; Maxwell's professorships were not absolutely necessary for him. I mention these cases as a parallel to that of the existing societies. They might be helped with a moderate subsidy which would be similar in its effects to a private person having some settled income, even if this applied only to that one matter of funds for publication. This would in its turn help a great many people who would be encouraged to send papers, which would now probably be refused owing to the fact that only matter of the highest standard can be published. It is also notorious that undue censoring in the past has refused or kept back for years some of the most important papers which workers have sent in.

Mr. E. H. Rayner (*communicated*): I have given the paper very thorough consideration, largely on account of the importance of the subject to the well-being of all branches of the electrical profession and industry and therefore to the Empire, and partly on account of the peculiar circumstances in which it has come before the Institution. The least one can do is to study such a paper most thoroughly and sympathetically before criticizing it. If the following notes cover much of the ground traversed by Dr. Rosenhain and others, they are put forward because they were made before the reading of the paper and without any knowledge of their views. The author states in the second column of page 135 that in Germany the smaller concerns have allowed themselves to be merged in great trade combines for the benefit of the nation as a whole. It may be so in some cases; but probably the cause is generally much the same as in other countries. The financial methods in Germany often resulted in the large banks having the real power in industrial matters, sometimes obtained by the common methods adopted by countries in which the conditions are favourable to the formation of trusts, and often by the firms requiring credit for working capital, which practically made them the property of the great banks. The altruism suggested in the sentence is, I think, of the same nature as that which impels the average school-boy to school on a fine summer's day. It is a question of control by superior power. The real point of importance is summarized at the bottom of the first column of page 138, where the author outlines the organization of his scheme "centralizing under one board or committee the control of all the research laboratories attached to the universities, colleges, and training institutions of the country, as well as of a large number of similar experimental laboratories connected with private works. . . . The board would have full powers to order any laboratory to undertake certain research work or to leave another research alone or to transfer equipment and personnel." Assuming the board were composed of the best possible individuals for the purpose, such a scheme sins against one of the fundamental conditions for healthy research, which is freedom. The type of research work which is commonly carried out at universities is very generally of

fundamental importance in physics or biology. An excellent example was furnished by the interesting discussion at the Joint Meeting last week with the Royal Society of Medicine. How can any board of men, however willing to help, be capable of instructing a Faraday, Clerk Maxwell, Kelvin, Helmholz, Rowland, John Hopkinson or Bertram Hopkinson, Michelson, Langmuir or J. J. Thomson, as to what branch of research they were to undertake, or to leave alone? Such a scheme would effectually suffocate real progress; and it is in addition suggested that the university should pay £500 a year. I venture to state that if such a board or a majority of the members of the Institution went round the laboratories most famous for their contributions to our knowledge of the fundamental properties of matter, whether physical, chemical or mechanical, they would learn but little of their secrets. Each research of importance demands new ideas tools and methods, which would be, as it were, a dead language to the majority of outsiders. It is important to realize what character would be assumed by researches carried on by a research board. The researches that will come under such a board as is suggested, will be such as individual firms have not been able to solve. They will have tried certain processes or methods for economic reasons with perhaps little or no success. The subject may be too abstruse or difficult, and be beyond their powers and plant. The board will therefore have put up to it, in many cases, problems which industry has been unable to solve. The difficulties will lie deeper and be more fundamental than they are equipped for. We must look to laboratories equipped with the outlook of those of Cambridge, Manchester or Schenectady for the foundations of our advances. In other words it is the laboratory with a staff with physical and chemical knowledge and imagination, that we must look to for the solution of our most difficult problems. Equipment for physical and chemical work is often more important than technical apparatus. I have spoken as to the necessity of freedom of research for laboratories of the university type, even under a board of ideal personalities. As to the type of board, I do not think the suggested scheme by any means satisfactory. Let us look at the scheme from a business point of view. The problems to be tackled will be those that are the most difficult at the moment. Who are those who can give most help in such work as research? I feel certain that the most help will come from those who understand best what research means, who have been through the mill of experience and realize how much effort and patience go to what may appear to be a very little result. A research establishment should be run largely by researchers, not without a sprinkling of the commercial side. The head must be primarily of a sympathetic personality, not necessarily a scientist. He must have an insight into character, and be ever ready to encourage and above all protect the brains working under him from the strangling effect of red tape. The suggestion that such an organization should be in any way controlled by members of Parliament [illegible] for their ability to control or even understand the meaning of the word 'research" than I possess. The writer suggests that positions on the board and on committees be honorary. This is a perpetuation of one of the most vicious arrangements in vogue in this country, and which has been indirectly responsible for much of the nation's indifference to science and its results, some of which we are discussing to-night. In general life one expects to get about as much of a commodity as one pays for; and if we pay nothing we ought not to expect much. It is to the honour of the scientist that he has often given his assistance, the fruits of his genius, for nothing. The Treasury has got into the habit of expecting it, and will tell us so, if we ask them. The consequence is that being paid nothing for his job, the Treasury have got into the habit of considering his opinion or result not worth much, and there is little public opinion to back up his claims. If we really want good work, we must, in general, pay a man for it, or we cannot expect a man to do his best, and his best is only what is worth having. He must have a heart in his work, or time, labour, and money will be wasted. As an example of our present methods, I heard of a man the other day who has a world-wide reputation, and who was a member of some 30 committees. Only about three of these really interested him. How can the best results be obtained when many of the remaining 27 committees were concerned with really important research work of the nature of those discussed in the paper? The war and its own special researches have opened the eyes of many of our most eminent mathematicians and scientists as to the way their abilities may be useful in practical problems of national defence to a degree which they did not expect. They may be assured that the problems of peace are equally urgent and far wider than those of war. It is for the industry to solicit their assistance in a proper manner, and to convince them that, though they often do not know it, their assistance is essential to satisfactory progress in the harnessing of the forces of Nature to the uses of mankind.

Mr. J. S. Highfield: I am sure this paper has served a useful purpose in producing this discussion to-night. I said at the beginning that the co-ordination of research was one of the most difficult subjects that we can deal with, and I think the discussion to-night has assisted matters. We cannot say more for a paper than that, and I am sure we are gratified that this paper was the one that secured the prize. I feel the greatest sympathy with those speakers to-night who have expressed doubt as to complete centralization. I am beginning myself simply to loathe the words "organization" and "co-ordination." They sound so impressive, and they really mean nothing. I think if the bodies of people and the individuals who have it in their minds to centralize everything into one great whole, controlled by one mighty brain from London, would only put themselves in the position of office-boy instead of the position of the central organizer, they would begin to see where the difficulties were. I am perfectly certain it is a waste of energy to try to centralize the whole business of research—in fact of anything else in this country full of Englishmen—and that we must separate things out and let the Englishman work on his own, as he has been used to doing. Further than that, I believe, as Mr. Paterson said, that over-

lapping is an extremely good thing. There is a certain sporting element in overlapping, and I think if an Englishman is to make any progress in research or anything else he must feel that there is a certain amount of sport at the back of it all—money is not sufficient. There must be that sporting element of rivalry between man and man; we get most of the progress in art and science and manufacture through that sporting instinct. One firm gets an article, and the next starts in to beat it; then the first firm tries again. I do not want to lose the value of the sporting instinct and its driving force. At the same time I think that the working together of different firms trading in the same sort of business is of very great advantage, and there is no doubt that, without any outside help, it has taken place in a large measure; they do work together in a way they did not before the war. I think much invention will originate in the works laboratories; it will not be published—not broadcast at any rate—but problems will arise in the works laboratories that can be helped by the university laboratories. There is no better form of instruction and education for students than to put them to research work, even if it be simple routine research work. I hope that the works laboratories when they come across problems, the ascertaining of constants and matters of that sort suitable for dealing with in the university and technical school laboratories, will set the problems to those laboratories, and that the laboratories will deal with those points. That sort of work—the determination of constants, coefficients of expansion and so on—can be published broadcast with every advantage, and therefore it is suitable for the university and technical school laboratories to deal with.

THE TELEPHONE SERVICE OF LARGE CITIES, WITH SPECIAL REFERENCE TO LONDON.

By E. A. Laidlaw, Member, and W. H. Grinsted, Associate Member.

(*Paper first received* 9 *January, and in final form* 1 *February*, 1919; *and read before* The Institution, 15 *May*, 1919.)

Summary.

The authors first consider the changes that have already taken place and are now in progress among the telephone-using public and in the labour and manufacturing worlds. The bearing of these changes on the possibilities of improvement in telephone service, on the adjustment of tariffs, and on reductions in expense is then discussed.

A proposal is made for the introduction of a "unit of telephone service" as the basis of the charge made to a subscriber. By taking the duration of the conversation into account, the charge would be scientifically proportioned to the expense incurred, yet without involving technicalities not easily understandable by the subscriber.

The consideration of the trend of events points to the introduction of mechanical appliances to effect the switching operations for all but those special cases of call for which expert attention is essential. The authors discuss the engineering aspect of the application of mechanical operation in the shape of "full automatic" working to large cities, and deal with the technical problems which arise both with the ultimate arrangements and particularly during the transition stages, taking London as a case presenting the maximum difficulty.

Synopsis.

Introductory. Object of paper to afford opportunity for discussion—changed conditions as affecting—

(i) The Public—greater need for best possible service—increased intelligence—tariffs.

(ii) The Operating Force—increased cost of and new fields for women's labour—attention now being paid to monotonous work, reduction of working hours, elimination of split duties, etc.

(iii) The Engineering Plant—improvement of manufacturing methods.

Need for consideration of the trend of events in order to secure economical expenditure of capital.

Effect of technical side of present changes in service, tariffs and expenses—changes in methods which can be made to meet the new conditions.

The quality of telephone service.—Subscriber's estimate as criterion of satisfactory service—accuracy—speed—distortion—transmission—absence of irregularities—the possibilities of improvements under each head.

Tariffs.—Ideal tariff—existing tariffs—the time element—proposed unit of telephone service—advantages—effect on load factor—summary.

Expenses.—Items of expenses—capital costs—interest and depreciation—revenue charges involved in replacing plant—maintenance—rents and other charges on buildings—administrative and operating charges—possibilities of reduction of expenses considered under each head—summary.

General discussion of application of mechanically-operated systems. As means of meeting changed conditions—comparison of semi-automatic and full-automatic systems from subscribers' and administrations' points of view.

Technical problems of automatic systems in large cities.—As illustrated by London—notes on London telephone area—development assumed—six-figure numbers—division into regions—names and numbers allotted to regions—discussion of typical region—completion of traffic originated within the region—sub-exchange problem—completion of traffic incoming to the region—cross-boundary traffic.

Problems of the transition period.—Change of numbers—stages of conversion—methods of handling junction traffic during transition period—trunk traffic—conversion of typical exchanges.

Concluding remarks.

Introductory.

Whatever value this paper may have does not lie so much in the paper itself as in giving a stimulus to and an opportunity for discussion of subjects which are, particularly at the present time, of great interest to the members of the Institution connected with telephone work.

The changed conditions due to the events of the last four years make it of interest to review the whole question of the provision of telephone service. We have attempted to outline and briefly discuss the more important of the matters which call for review, in the hope that all of us may gain clearer ideas of the meaning and effects of these changes, and undertake our work during the strenuous years of reconstruction on sound lines and in a way worthy of the position of our country and our empire. We have chosen the case of large cities not only because it is the case of most importance, but also because in them practically all the details of the problem are met and have to be dealt with.

The last 20 years have seen the introduction of lamp signalling and central battery switchboards, which passed through their experimental stages in America and were then introduced into this country. They have now replaced the earlier equipments in a number of our large cities. The service rendered by them is a great improvement on that given on the old equipments, but it has remained at almost the same level since their introduction. At the present moment it

is certainly worth while to consider what improvements in service and economies in operation may be anticipated during the coming period of, say, 20 years from now.

Conditions have changed, and are still changing, in a way which affects all of the three main factors concerned, namely, in the authors' opinion, the public, the operating force, and the engineering plant.

Public.—The prosperity of this country in the near future will depend entirely upon the efficiency and energy of our commercial undertakings. The telephone is admittedly one of the greatest aids to rapid and effective prosecution of business affairs, and there will be demanded of it service of the highest possible standard. The subscribers in our large cities will be impatient of anything short of the best that modern methods can render, and any shortcomings due to plant of obsolete type or to out-of-date methods will be looked upon as inexcusable.

The telephone-using public is not that of 20 years ago; there is almost the difference of a generation, and the present-day public is better educated, more intelligent, and familiar with mechanical and electrical devices of all kinds. Labour-saving appliances, some of them of the most elaborate nature, are common in all classes of business and are used with success by employees of all ranks.

The question of tariffs, too, is one which affects greatly the extent to which the telephone service can be developed towards the ideal. The introduction of the measured rate has been beneficial, in that it has placed the tariffs on a sounder basis and avoided the injustice of making the small user pay for part of the large user's service. Its disadvantages, however, have not been escaped: it has tended to prevent the use of the telephone for short and relatively unimportant communications; and further, the introduction of junction fees which accompanied it has brought about a reduction in the operator's load and has involved administrations in a large amount of ticket sorting and clerical work. This disadvantage will be accentuated in the future, for the changes in conditions, which are described below as referring to the operating force, also apply to the labour for this work.

Operating force.—There has been recently a large rise in the cost of labour and it is certain that there will be no corresponding fall to anything approaching the "pre-war" figures. This applies to labour of all classes, but its effect will be particularly felt in the case of the operating force.

The operating force is also likely to be affected by other changes which are taking place. Many new fields are now open for women's labour. Examples will readily occur to all, but the authors would mention particularly clerical work in banks, Government and insurance offices, once almost entirely reserved for men, but open for the future to the class of woman from which the best operators are drawn.

A great deal of attention is now being paid to the effect of monotonous and nerve-straining work of all kinds, and public statements have been made * classifying telephone operating under this description. Whether this is correct or not, it is certainly the case that the relief afforded by some classes of monotonous labour is not to be found at the switchboard. The remedies proposed for the effects of monotony are also scarcely applicable to the bulk of telephone operating. It is hardly possible to encourage initiative or to provide alternating forms of employment in order to give interest and variety.* More frequent periods of rest, and an even higher standard of comfort and provision for recreation in the operators' quarters than at present, seem to be the only practicable means of affording greater relief. The authors do not necessarily consider that an increased provision for comfort and recreation is justified, but are pointing out the tendencies towards such an increase. Such an increase would, of course, carry with it increases in the expenses for rent, etc., which are already high, particularly in large cities.

Investigations undertaken by the Health of Munition Workers Committee † have led to a great deal of discussion as to the desirability of reducing the number of working hours per day, and it has been shown decisively that in many cases such a reduction results in less lost time and in an increased output even for the shorter day. Steps to shorten the working day have already been taken in many factories. In telephone operating, it is possible that there will be less time lost due to sickness, but owing to the nature of the work it is scarcely likely that the number of connections handled by an operator per busy hour or per day could be increased as a result of reducing the number of hours worked. Should such a reduction become general in women's labour, however, it is probable that administrations, in common with other employers, will be forced to reduce the operators' working hours.

Objections are being raised also to split duties, shifts, and night work. Duties of this nature are particularly difficult in large cities owing to the work being remote from the operators' homes.

Although there may be no good reason for applying to operators' work some of the extreme recommendations which have been made by various Committees, telephone administrations, particularly Government administrations, will be obliged, if only for the sake of setting an example, to give effect to those which meet with general approval.

Summarizing the tendencies of the age as they affect the operating force, it may be said without fear of contradiction, that labour for it will be considerably more expensive, more difficult to obtain, and more exacting and inflexible as regards the arrangement of its duties and the provision for its comfort than in the past. On the other hand, there is very little sign that the number of calls handled per operator hour will increase; in fact, the experience of the last few years points in the other direction.

Engineering plant.—Upon the engineering plant of a telephone system the continued application of scientific discoveries and the improvement of manufacturing methods are having, and will continue to have, a marked

* Report No. 379, U.S. House of Representatives; Extension of the Telephone System in Columbia, p. 9. "The work of the operator involves such arduous application and nervous strain as alone to justify its elimination."

* Interim Report on Adult Education; Ministry of Reconstruction. Cd. 9107, p. 14.

† Interim Report on Industrial Efficiency and Fatigue (Cd. 8511). Also Memoranda Nos. 5, 12 and 20 of Health of Munition Workers Committee.

effect. As an instance of applied science, the amplifier stands pre-eminent. It is certain to modify considerably the design of long-distance line plant.

Improvement of manufacturing methods is likely to have a more direct effect upon the design of the exchange plant. During the last decade a great stride has been made in economical and rapid methods of manufacture. This has been accomplished by the use of elaborate tools, necessitating that the articles dealt with should be required in large quantities. In the past this country has met its requirements for articles of this nature largely from foreign sources. There has been, however, during the war an enormous increase in facilities for manufacturing mechanical products, and we should be now in the position not only to be self-supporting in this field, but also to manufacture for export.

General.—It has been adopted as a principle of telephone engineering that an efficient and economical service can only be provided if all the needs of future development are carefully studied and adequate provision made to meet them. But it is also necessary, particularly at this period of change, for the telephone engineer to consider not only the development of the telephone system, but also the trend of events in the labour and manufacturing worlds, if he is to secure economical expenditure of capital and avoid investment in plant which may become obsolete before it has reached the end of its useful life. Bearing in mind these changes and the directions in which they tend, let us pass on to consider how they affect

(*a*) possibilities of improvement in the quality of service,
(*b*) adjustments of tariffs,
and (*c*) possibilities of reductions in expense,

and to discuss what changes in methods and practice can be made to meet the new conditions.

The Quality of Telephone Service.

Criterion of a satisfactory service.—The subscriber's estimate of the telephone service may be somewhat indefinite, yet it is the only real criterion of a satisfactory service. It is based upon the ease with which he obtains the connections he desires, upon the reliability and freedom from interference of the connection when established, and upon the speed with which he can obtain further connections. These factors are more or less measurable and have been adopted by administrations as the basis for defining the quality of the service. There is no doubt that the subscribers' definition is broader. It embraces many factors which are not included in the limited scope of the administration's service observations. The subscriber, too in including each factor in his estimate, unconsciously weights it according to the way it affects him. This is a process which it is impossible to apply satisfactorily to service observation results. The authors do not wish to suggest in the least that service observation is of little value. On the contrary, it is extremely useful and has already been responsible for many improvements in the quality of service. But it cannot be overlooked that it ignores certain factors which are by no means all that the subscribers understand by "service."

The authors propose first to consider what improvement is possible in those items which are dealt with by the observation records.*

Accuracy.—The errors by which calls are affected on large modern central-battery systems are usually classified under:—

Cut-offs;
Connections to wrong lines;
Double connections;
Incorrect reports (Am.).

These affect, even on the best operated equipments, 2 to 5 per cent of the local calls, and up to 9 per cent of the junction calls (Am.).

In addition, there are operating irregularities, classified under:—

Improper repetition;
Improper phraseology;
Careless supervision;
Operator impertinent or discourteous (Am.);
Miscellaneous irregularities.

These affect some 7 to 10 per cent of the calls. Of certain of these irregularities the subscriber would take no account; others, however, would cause him great annoyance and influence very considerably his opinion of the service.

The figures quoted apply to systems in large cities having central battery equipments of modern type, with monitors' and supervisors' equipment, and other aids to effective operating and supervision, operated in accordance with the latest practice.

Without changes in the type of equipment, an improvement in these figures might be obtained by lowering the operator's load. This involves an increase in the number of positions and makes the operating at slack times even more inefficient than at present. Other measures might be to subject the operators to more strict supervision, to recruit a better grade of staff, and to train them more highly. The future holds little prospect of applying any of these remedies with economy.

Possible modifications in equipment having for their object the assistance of the operator may effect some slight improvement, in that they relieve her of certain movements; for instance, to give the calling subscriber "number engaged" and "ringing" tones, thus relieving the operator of the necessity of advising him verbally, may eliminate a certain number of incorrect reports. Other modifications such as call distribution, keyless listening on A positions, keyless ringing on B positions, and automatic order wire distributers, may assist in so far as they enable the operator to do her work more systematically, but their effect on the accuracy of the service must be slight, particularly when advantage is taken of the increased load which these auxiliaries

* The headings under which the service observations are classified and the figures quoted refer to the practice of service tests at 10 Am country in all cases where the authors are acquainted with them. In other cases they have drawn upon the figures for American service under pre-war conditions, published in Table 15, Report No. 156, Part 2, U.S. House of Representatives, Investigation of the Telephone System in Columbia, and in Table 7 of Mr. McCarthy's paper, *Journal I.E.E.*, 1917, vol. 55, p. 288. These figures are kindly by Mr. Ellis (Am.).

are intended to afford. Other recent introductions having as their object an increased load, such as ancillary answering jacks, are, the authors imagine, positively harmful to accuracy.

Each of these errors and irregularities, when traced to its source, arises from an operator doing something which she ought not to have done. Modifications in equipment will not remove this human tendency to err; they can only lessen it.

Systems in which the operating is effected mechanically, that is, "automatic" systems, are not subject to errors of this nature. It is true that they introduce other sources of error which are discussed later, but they are free from each and all of the errors and irregularities referred to above with the exception of an extremely small percentage of connections to wrong lines and double connections.

No considerable improvement in the accuracy of the service, therefore, can be expected from equipments of the manual type. For an improvement in this essential, we must look to the introduction of mechanical operation.

Speed.—Under this heading, the following are the main items recorded by the service observation clerk as referring to the establishment of the connection. The authors have inserted against the items figures representative of the standard service aimed at on modern equipments in this country.

(*a*)	Average time to answer calling signal	5 secs.
(*b*)	Percentage of calls in which answer is delayed more than 1 second after plugging in	1·5 % (Am.)
(*c*)	Percentage of calls answered in under 2 secs.	5 %
	Percentage of calls answered in under 3 secs.	20 %
	Percentage of calls answered in under 4 secs.	50 %
	Percentage of calls answered in under 5 secs.	75 %
	Percentage of calls answered in under 10 secs.	95 %
	Percentage of calls with answering time greater than 10 secs. ..	5 %
(*d*)	Average time from commencement of call until called subscriber answers :—	
	Local call	25 secs.
	Junction call	35 secs.

Before considering what improvement is likely to be possible in these elements, let us try to realize exactly how they affect the subscriber's impression as to whether the service is satisfactory or not. The subscriber is concerned with getting a reply from his correspondent as quickly as possible, so that the figures under item (*d*) are those which are really of the greatest importance from his point of view. At the same time, he desires a short "time of answer" to assure him that the administration is giving him prompt attention. In forming his opinion of the service, the subscriber is influenced far more by extremes than by the average figures. This is the reason why the average time of answer, item (*a*), is supplemented by an analysis under item (*c*). It is instructive to make a similar analysis for the figures under item (*d*). Such an analysis shows the following percentages :—

TABLE 1.

Local Calls.

Analysis of 2,010 Calls in Four Different Cities.

Percentage of calls on which called subscriber answers in under		10 secs.	3 %
Ditto	ditto	15 secs.	20 %
Ditto	ditto	20 secs.	36 %
Ditto	ditto	25 secs.	64 %
Ditto	ditto	30 secs.	77 %
Ditto	ditto	45 secs.	91 %
Ditto	ditto	60 secs.	96 %
Ditto	ditto	90 secs.	98 %
Ditto	ditto over	90 secs.	2 %

Average time, 26·6 secs.

TABLE 2.

Junction Calls.

Analysis of 2,480 Calls in Four Different Cities.

Percentage of calls on which called subscriber answers in under		15 secs.	4 %
Ditto	ditto	20 secs.	22 %
Ditto	ditto	25 secs.	39 %
Ditto	ditto	30 secs.	53 %
Ditto	ditto	40 secs.	74 %
Ditto	ditto	60 secs.	88 %
Ditto	ditto	90 secs.	98 %
Ditto	ditto over	90 secs.	2 %

Average time, 38·8 secs.

Part of the period considered in the above tables is the time until the operator commences to ring the wanted subscriber. The remainder is the time taken by him to respond to the ring. Only the first part is entirely under the control of the administration. For the time taken by the subscriber to respond, although it may be influenced by the method of ringing, the administration is not directly responsible. It would be of great interest to analyse the first part in a similar way, but since the time when ringing is commenced cannot be observed by the observation clerk on outgoing calls, no figures bearing directly upon this time are available. Records of the time taken for the subscriber to respond are, however, made upon incoming calls and it is possible, by applying these to the analysis given in Tables 1 and 2, to obtain indirectly a fairly exact analysis of the time elapsing till the subscriber is first rung. This is given in Tables 3 and 4.

The extreme delays are in many cases due to operating errors, such as ringing wrong numbers, for in observing the service the time noted is that taken to ring the correct subscriber.

It is the period considered in the last table which is important from the subscriber's point of view, and is directly under the control of the administration.

An improvement is to be looked for in two respects, first a shortening of the average time taken to ring the wanted subscriber, and second, a greater uniformity in this time; for as we have pointed out above, it is the extreme delays which influence the opinion of the calling subscriber.

Such measures as were considered under "Accuracy" might effect improvements, but here again the improvement can only be obtained at considerable expense and by the sacrifice of the advantage of the increased load which alone would justify modifications to aid the operator.

The introduction of mechanical apparatus for completing exchange calls would eliminate the great difference shown in the figures above between local and junction calls. It would bring the service on all calls up to the

TABLE 3.

Local Calls.

Percentage of calls on which called subscriber is first rung in under		10 secs.	16 %
Ditto	ditto	15 secs.	42 %
Ditto	ditto	20 secs.	81 %
Ditto	ditto	25 secs.	88 %
Ditto	ditto	30 secs.	92 %
Ditto	ditto	45 secs.	97 %
Ditto	ditto	60 secs.	98 %
Ditto	ditto over	60 secs.	2 %
Average time, 16·4 secs.			

TABLE 4.

Junction Calls.

Percentage of calls on which called subscriber is first rung in under		15 secs.	20 %
Ditto	ditto	20 secs.	41 %
Ditto	ditto	25 secs.	62 %
Ditto	ditto	30 secs.	76 %
Ditto	ditto	40 secs.	86 %
Ditto	ditto	60 secs.	95 %
Ditto	ditto	70 secs.	98 %
Ditto	ditto over	70 secs.	2 %
Average time 28·6 secs.			

level of that shown for local calls, thus not only shortening the average time but making the service more uniform. A further improvement would result from the extension of mechanical operation to the completion of both local and junction calls, i.e. "full automatic" working. On the system not only is the average time until the called subscriber is rung shortened, but it becomes almost exactly the same for all calls and extreme delays are eliminated. Table 5 shows an analysis of full automatic service on the same lines as those referring to manual service above. The figures in the first column are from statistics for a number of different exchanges, some having four-figure and some five-figure numbers. In order to give some idea of what might be expected in an extremely large system such as London, for which six trains of impulses would be necessary, we have in the second column increased the time by 2 seconds, thus making more than ample allowance for the time taken to dial the additional digits.

TABLE 5.

All Calls.

Percentage of calls on which called subscriber is first rung in under		From statistics	Estimated for 6-figure system
	3 secs.	20 %	—
Ditto	5 secs.	47 %	20 %
Ditto	8 secs.	82 %	70 %
Ditto	10 secs.	88 %	81 %
Ditto	15 secs.	93 %	91 %
Ditto	20 secs.	95 %	94 %
Ditto	25 secs.	97 %	96 %
Ditto	30 secs.	98 %	97·5 %
Ditto	over 30 secs.	2 %	2·5 %
Average time	.. ..	8 secs.	10 secs.

Disconnection.—The speed of disconnection is an element of the service to which considerable attention is paid in service observation. It is of particular interest to the busy subscriber that he should be able to make a further call or that his line should be made free for incoming calls without delay.

The observation records deal with this element under the headings:—

Average time to answer a flashing supervisory signal	5 secs.
Average time taken by operator to disconnect	5 secs.
Percentage of calls in which time taken to disconnect is over 8 secs.	2 % (Am)

On about 10 per cent (Am) of the calls, it is necessary for the subscriber to call in the operator by flashing the supervisory signal either to make a further call or to report some difficulty. Although 5 seconds may appear to be a reasonably short time for the disconnection or for recalling the operator, it does not represent accurately the state of affairs as viewed by the subscriber. In the first place, if the call has been one incoming from another exchange, the average time taken to disconnect and free the line becomes 10 seconds. To establish a further exchange connection in this case, the subscriber has then to await the attention of his local "A" operator. He is in these circumstances specially sensitive to delay. Moreover, he rarely flashes the supervisory signal at the correct speed, and in a number of cases gives up the attempt and waits for his line to be disconnected.

Delay in disconnecting has also an indirect effect upon the service in increasing the time during which the lines test "engaged," and so increasing the percentage of "number engaged" reports.

In spite of its drawbacks, flashing the supervisory signal from the subscriber's switchhook cannot very well be abandoned without modifications to the exchange equipment, for should the subscriber remove the receiver to make a further call before the operator has disconnected, his supervisory signal is extinguished and fails to attract the operator's attention.

In America, modifications in the cord circuits have already been introduced, providing what is known as "instantaneous re-call." The circuit is so arranged that, if before the connection is cleared the receiver be again removed, the supervisory lamp is connected to an interrupter and continues to flash until the operator comes into circuit. This eliminates incorrect flashing on the part of the subscriber, but it does not remove the delay in attracting the attention of the operator.

Other extensive modifications of manual central battery equipments have been proposed to provide "instantaneous disconnection," that is, release of the line and its reconnection to the calling equipment immediately the receiver is replaced. This would very greatly improve the service as far as the element which we are considering is concerned. But it is difficult to see that it would effect any reduction of operating expense, and it is doubtful whether it would be justifiable to incur the additional cost in equipment for a scheme which would result in an improvement of the service in this one particular only, leaving untouched many other points in which improvement is possible.

The elimination of delays in disconnection and in the establishment of further connections is an improvement which is afforded in a high degree by mechanical operation. Systems on this principle can be arranged so that the release of each subscriber's line and its reconnection to his calling equipment follow directly upon the replacement of his receiver. The full benefit of this feature is not, however, obtained at present on some public automatic systems which are so arranged that the release of both lines is controlled by the calling subscriber. The connection is cleared and the called subscriber's line freed only when the calling subscriber replaces his receiver. Failure to release within a reasonable time is provided against by a delayed alarm signal in the exchange.

The extent to which this arrangement detracts from the full advantage of instantaneous disconnection is, however, quite small. The following figures show the results of observation on some 937 calls :—

Percentage of calls in which called subscriber's line becomes free without any delay	76 %
Ditto in less than 1 sec.	87 %
Ditto in less than 2 secs.	92 %
Ditto in less than 3 secs.	94 %
Ditto in less than 5 secs.	95 %
Ditto in 5 secs. or more	5 %

Out of the 5 per cent of calls on which the delay exceeded 5 seconds, 3 per cent were subject to delays up to 1 minute or more. In a number of these cases the connection was traced back and the cause ascertained. In the large majority of the cases so examined it was found that the operator at a distant manual exchange, the junctions from which were connected to ordinary subscriber's calling equipments, had failed to disconnect.

These observations were made on an exchange with about 1,000 working lines and having a relatively small number of private branch exchanges connected to it. On an exchange with many private branch exchanges one might expect results not quite so good owing to the private branch exchanges' operators failing to clear promptly on calls originated by them.

Transmission.—Once connected with his correspondent, the subscriber desires easy speech and clear reception, with freedom from noises, clicks, cross-talk, and overhearing.

The standards of construction to which modern administrations are working are such that no striking improvements are likely to be made. Future development is more likely to have its effect upon the methods of attaining these standards than in raising their level.

Large cities offer special problems in transmission owing to :—

(*a*) the density of the subscribers, making desirable conductors of as small diameter as possible ;
(*b*) the number of exchanges, tending to increase transmission losses ;
(*c*) the large area over which a common interest extends, tending to create a large percentage of connections through two or more exchanges and involving junction lines of considerable length.

Two means are available of compensating for the transmission difficulties due to the use of small conductors and the length of the junctions One is the application of loading to the junction circuits ; the other is the employment of a higher voltage than has been standard for the central battery in all exchanges in the past. The application of loading in large cities is not easy on account of the difficulty in finding space for the coils and the special arrangements required at the exchanges to limit signalling and testing currents to values which will not affect the coils. The gain in transmission obtained by loading comparatively short lines does not approach that obtained on long trunk lines.

The increase of voltage, however, seems to present advantages in every way. It permits a greater maximum resistance for the subscribers' lines and, to a certain extent, reduces the local line sending allowances. The resistance of the feeding bridges in the cord circuit is higher, so that the sending allowance is not so dependent upon the resistance of the line. The impedance of the feeding bridges may be made much greater for the same size of coil, so reducing the losses due to the shunting of the speech currents. Long junction lines may be worked without the special long line equipments necessary for signalling purposes, thus removing a fruitful source of transmission loss. In addition to improvements in transmission, the higher voltage affords larger margins on the operating requirements of the relays, and so reduces maintenance expense.

Naturally an increased amount of energy per call is taken from the central battery, but the cost of this, as well as any slight increase in the capital costs which can be ascribed solely to the increase in voltage, should be, the authors think, more than compensated for by the transmission and maintenance advantages.

It has already been necessary to introduce an increased voltage for operating junction circuits, and

the adoption of a standard voltage for all manual exchanges has been foreshadowed.*

The automatic exchanges in public use all employ a voltage considerably higher than 22 volts. It is possible that one voltage could be standardized for both manual and automatic equipments. The benefits in the reduction in the number of different types of relays, lamps and other apparatus, would be considerable both to the administration and to the suppliers of exchange plant.

There is therefore a possibility of effecting some improvement in transmission in our large cities by adopting universally a voltage higher than 22 volts.

Absence of irregularities.—Operators' irregularities are dealt with under the heading "Accuracy," and under this heading are included all those other irregularities which make a service unsatisfactory from the subscriber's point of view.

One of the chief of these is the "number engaged" trouble. The percentage of calls on which the subscriber receives this report varies from 10 per cent over the whole day on moderately busy exchanges up to nearly 20 per cent during the busy hour on the busiest exchanges. Another item is the "no reply" report, which is given on about 2 per cent of the calls.

Some 2 per cent of the incoming calls to a subscriber are cases in which he is "called in error" (Am.).

Wrong numbers given by subscribers, subscribers replacing the receiver before the conversation is finished, or failing to replace it at the end of the conversation, and similar bad operating at private branch exchanges, affect another 2 per cent of the calls.

A small percentage of calls is affected by maintenance or plant troubles and congestion on junction groups. This, however, does not amount under modern conditions to more than a small fraction of 1 per cent.

A reduction in the number of these irregularities is not altogether in the hands of the administration. The most important is the "number engaged" trouble. Under modern tariffs it may be assumed that each subscriber has a number of lines sufficient for his telephone business. An improvement is only to be sought, therefore, in reducing the length of time each line is engaged, particularly during the busy periods. The holding time may be reduced by reducing the time taken to set up the connection, by improving the quickness of answer on the part of the called subscriber, and by reducing the time of disconnection.

	Manual local calls secs.	Junction calls secs.	Automatic 6-figure system secs.
Originated Calls.			
Average time elapsing from removal of receiver until called subscriber is rung	10·4	28·6	10
Deduction on manual calls time before operator plugs in and applies engaged test	4·0	4·0	—
Leaving	12·4	24·6	10
Time taken by called subscriber to respond	—	Equal for all calls	
Duration of conversation	—	Taken as equal	
Time taken after replacement of receiver until engaged test is removed by operator withdrawing answering plug	5	5	0
Totals	17·4	29·6	10
Reduction in time of engagement afforded by automatic equipment	7·4	19·6	—
Average ditto with 80 per cent junction working		17·2 seconds	
Incoming Calls.			
Time taken by subscriber to respond		Equal for all calls	
Duration of conversation	—	Taken as equal	
Time taken after replacement of receiver until engaged test is removed by operator withdrawing calling or junction plug	5	10	0
Reduction in time of engagement afforded by automatic equipment	5	10	—
Average ditto with 80 per cent junction working		9 seconds	—
All Calls.			
Average assuming equal originated and incoming calls	—	13·1 seconds	—

As we see under the heading "Speed," there is little hope of improvement in these items, without a change in the type of equipment. Automatic equipment, however, promises a considerable reduction in the time of engagement, other than that occupied in conversation, as the above comparison shows. The figures are extracted from Tables 3 to 5.

It will be noticed that no difference has been made in respect of the decrease in the duration of the conversation, amounting in some cases to as much as 40 per cent, which has been observed when an exchange is converted from manual to automatic working.* The cause of this decrease has, as far as the authors know, not yet been determined, but its effect on the time of engagement is probably nullified by the increase in the number of calls.

* Address on "Telephones" by Sir W. Slingo, Institution of Post Office Electrical Engineers, 8 November, 1915.

* F. R. McBerty, *Journal I.E.E.*, 1917, vol. 55, p. 288.

Assuming a 2-minute conversation, this would represent approximately a 10 per cent reduction in the time of engagement.

A reduction in the duration of the conversation might be effected by the introduction of a tariff taking account of the time element. The distribution of the traffic over the whole of the day might be encouraged by reducing the rate at which the calls are charged during the slack periods. Such a tariff is dealt with later in the paper. The measured rate tariffs at present in use contain no feature which tends to improve the "ratio of day to busy hour." They are also of a nature to encourage lengthy conversations, though it is probable that this effect is not noticeable except in residential areas.

The discussion under the heading "Accuracy" applies to the item "Called in Error," in so far as this is due to operators' irregularities. Careful maintenance of the marking of the multiple, and a reduction in the distance to which the operator must reach, are the remedies which would effect a reduction. On modern equipments these points are already receiving attention.

The irregularities due to subscribers and private branch exchange operators form a class for which, it may be claimed, the administration is not responsible. But this view cannot be entertained. It is the duty of the administration to analyse the reports of trouble due to these causes as closely as those due to others, and to modify its methods and equipment to reduce all sources of dissatisfaction to a minimum as far as this can be done economically.

The full automatic system, whatever improvements in service it offers in other respects, is open to the charge that it will increase the number of calls affected by subscribers' irregularities, on account of errors in dialling.

Mr. McBerty * gives the result of 3,151 service observations from which it appears that the calls affected by subscribers' errors amounted to 1·02 (presumably per cent). The following are the results of similar observations on other equipments:—

Type of system	No. of calls observed	Subscriber dialled incorrectly		Wrong number connected		Total wrong nos.
		No.	%	No.	%	%
Automatic with little junction working..	8,513	84	0·99	26	0·31	1·30
		Sub. called wrong number		Oper. connected wrong number		
Manual with little junction working	4,596	44	0·96	43	0·94	1·90
Manual with about 60 per cent junction working	5,686	57	1	108	1·9	2·9
Very large manual system with 85 per cent junction working	16,531	141	0·85	774	4·7	5·55

It appears from these records that no greater number of subscribers' irregularities is to be expected with the full automatic system than with the manual system, and that the total amount of wrong number trouble, when that due to the operators is included, is likely to be considerably less. The increase of wrong number trouble with the amount of junction working is noticeable in the case of the manual exchanges. It can reasonably be expected that there will be no such increase with automatic systems in which the operation is precisely similar for both junction and local calls.

Summary.—The authors have examined in the foregoing section the effect of the changes through which we have passed and are still passing on the possibilities of improvements in the quality of service. They have tried to consider the matter as much as possible from the point of view of the telephone-using public. The public may not be competent to decide the methods by which its connections are to be completed, but the public has to pay and it is presumably for the benefit of the public that the telephone business is conducted. Telephone service is a service rendered to and paid for by the public, and it is not those who render a service, but those who are served, whose opinion of the quality of the service must ultimately be accepted.

We have seen that, without a departure from the types of equipment at present standard, there are two possibilities, namely, to improve the operators and to improve the equipments; neither alternative presents a hopeful prospect of effecting improvements in the service, especially when the large increase to be expected in the complexity and size of the telephone system is considered.

Operators are already carefully selected, schooled at considerable expense, highly trained and efficiently supervised, so that little more can be expected from them in the future than in the past. Present types of switchboard equipment have been standardized as the result of many years' experience, and even the refinements in design which can be applied with a view to effecting improvements in service are scarcely admissible from the economical standpoint.

Turning to the possibilities afforded by newer methods of operation, we find that sufficient experience has been accumulated to show that mechanical operation will afford a service of improved accuracy and speed, particularly in those items which appeal to the public. As the comparison in Table 6 shows, assuming 80 per cent junction working, the called subscriber's bell is rung in an average time of 10 seconds, as against 26·2 seconds on a call with manual service. 98 per cent of his connections are completed to this stage in 30 seconds, against 68 seconds with manual service, and he can free himself and establish a second connection with no delay whatever.

The use of mechanical operation has also a favourable

* *Journal I.E.E.*, 1917, vol. 55, p. 303.

effect on the number of irregularities, particularly upon the "number engaged" trouble. Experience shows that the wrong numbers called by subscribers with the dial are 1·3 per cent, while in similar exchanges those called by the subscriber and the operator amount to 1·9 per cent. On systems in large cities the difference would be even more marked. Cut-offs and double connections occur less frequently, particularly where there is a considerable amount of junction working.

The fear that the subscriber would prove incapable of handling the dial correctly has proved groundless. As the figures quoted show, the combination of subscriber plus dial gives rise to fewer errors than the combination of subscriber plus telephone plus operator.

TABLE 6.

Table showing Percentage of Calls in which the Called Subscriber is First Rung in less than a Given Time.

Seconds	Manual calls		Automatic calls, 6-figure system
	Local	Junction	
	%	%	%
5	Nil	Nil	20
8	5	Nil	70
10	16	3	81
15	42	20	91
20	81	44	94
25	88	62	96
30	92	76	97·5
35	95	82	—
40	96	86	—
45	97	89	—
50	97·4	91	—
55	97·8	93	—
60	98	95	—
65	—	96·5	—
70	—	98	—
Average	16·4 secs.	25·6 secs.	10 secs.
Average for 50 per cent. junction working ..		26·2 secs.	10 secs.
Time to complete 98 per cent. of connections ..		68 secs.	50 secs. (approx.)

There appears to be therefore little hope of effecting improvements in the quality of the service with the existing manual types of switching equipment. Mechanical operation, however, offers improvements in almost every item.

TARIFFS.

Ideal tariff.—A tariff, in order to be ideal from the commercial standpoint, should be proportioned to the expenses in every respect, so that the cost incurred in giving the service rendered on each call is covered by the revenue received in respect of that call. This cost is made up of (i) costs individual to the subscriber, comprising the annual charges on his line and instrument, and that part of the exchange equipment of which he has the sole use; (ii) costs of setting up the connection, comprising the operating charges and the corresponding building and administrative expenses; (iii) charges on the common connecting plant, comprising the annual charges on the junction plant and, in the case of mechanical operation, on the whole of the connecting plant not individual to the subscribers' lines.

Remarks on existing tariffs.—The old "flat" rate tariff was based solely on the first item. It ignored the fact that the service given to different subscribers might vary considerably in the cost of setting up the connections and in the use made of the common connecting plant.

The "message" and "measured rates" take account of this by charging a certain amount per annum to cover the first item and varying the remainder of the payment according to the number of connections set up. The third item is covered roughly by charging "junction fees" when specially expensive routes are brought into use. On trunk calls where the charges on the connecting line are the main item of expense, the rates per call are fixed according to the distance and the duration is limited to 3 minutes.

Time element.—In cities with large junction networks the charges on the common connecting plant form an important part of the expenses. They become even more important on mechanical switching systems in which not only the junctions, but also the bulk of the exchange plant, is provided on a basis of the maximum number of connections likely to be in progress simultaneously.

The only equitable way of allocating the expenses of this common plant is in relation to the amount of it brought into use and the time of its use for each connection. The desirability of taking into account the element of time has long been recognized.* The obstacle to its introduction has been the lack of a simple method of recording the duration of the connection and charging for it at a rate corresponding to the amount of plant brought into use.

Proposed unit of telephone service.—The problem is much simplified by the acceptance of the principle of a "unit of telephone service" as a basis for the variable part of the charge made to the subscriber. Suppose, for example, for a direct exchange line, a subscriber is charged a fixed annual sum in respect of the plant individual to him and then is charged a further amount for service at the rate of so much a "unit," the unit corresponding, say, to 1,000 local calls each of 2 minutes' duration.

The meter which records the units consumed is assumed to be in operation continuously during the conversation, and the rate at which the units are consumed on any given connection can be varied according to the amount of plant involved. For example, a unit might be made up of 1,000 2-minute local calls, or 500 4-minute local calls, or, say, 800 2-minute junction calls each equivalent to 1·25 local calls, or 500 2-minute long junction calls, each equivalent to

* J. E. Kingsbury, "The Telephone and Telephone Exchanges," pp. 418, 421.

two local calls, and so on. In fact, a subscriber would be charged for his telephone service almost in the same way as for his electric light, which he consumes for varying times and at rates varying according to the apparatus he brings into use.

Advantages.—This method of charging is scientific and fair, simpler than the message or measured rate, and will be readily understood and appreciated by a public already accustomed to similar methods of charging for electricity and gas. In addition, it lends itself readily to correct adjustment of the junction charges, which may be made any desired multiple of the charge for a local call, and it ensures that junction and, in fact, all calls of long duration are properly charged. It renders unnecessary the special ticketing or other method of recording such calls, and does away with the expense involved in the resulting lowering of the operator's load and in sorting the tickets, an expense which must inevitably increase as the exchange network becomes more complex and clerical labour more exacting. It very considerably simplifies the problem of automatically registering special fee calls on mechanically operated systems.

Effect on load factor.—By making arrangements such that the rate of recording on all meters can easily be altered, differential rates for different times of the day can easily be arranged. This permits attention to be given to a point to which little has been paid in the past, namely, the telephone "load factor" or the "ratio of the busy hour to the day," and the shape of the load curve. The plant, whether manual or automatic, has to be provided on the basis of the busy hour or peak traffic, and the bulk of it earns little revenue at other times. By reducing the rate of recording at the slack periods of the day (and perhaps by increasing it during the busy periods) the load factor might be improved and the plant brought more fully into use during the whole day, just as is done with the telephone trunk and telegraph cable services by means of their night and deferred rates. Any improvement in the load factor would have a considerable effect on the cost of providing exchange and junction equipment for large cities. Further, the reduced rates for the greater part of the day would lead to a much increased use of telephone communication and would undoubtedly appeal strongly to the small user.

Checking accounts.—As the meter would still continue to be fitted in the exchange itself, the objection might be raised that a subscriber has no means of checking its record, since this no longer depends simply upon the number of calls made. This objection might equally well be raised against the current methods of charging for electricity and gas, for although the meters for these services are on the consumer's premises, he has no means of checking the consumption registered, nor is any distinction made in his bill between the consumptions on different types of apparatus. The telephone subscriber might be afforded the same protection as the electricity or gas consumer, namely, a certification of the correctness of his meter and metering circuit by an independent authority (e.g. the Board of Trade) on demand and payment of a similar fee.

Summary.—The principle of the "telephone unit" has been put forward here for discussion as a proposed basis for future tariffs because it appears to eliminate the inevitably increasing difficulties felt with the existing methods of charging, and to be capable of being applied in such a way as to secure a greater revenue-earning efficiency from the plant. Further, it solves in a very satisfactory way many of the metering problems arising with mechanical operating. Its practical application is not without its difficulties, but the investigations already made, although retarded by the war, have advanced sufficiently to demonstrate its practicability.

Expenses.

General.—Under the present conditions any exact analysis of expenses is of little value. Capital costs, interests, and depreciation, and administrative and operating expenses, are undergoing revision from day to day, so that the figures to be used for making any such analysis would not be likely to meet with the entire agreement of anyone.

What can be examined with advantage, however, is the general direction in which each quantity concerned is varying, and the probable effect of this variation on the expenses of giving service with different systems.

Items of expenses.—Before discussing the effect on each different item of expense, it will be well to consider broadly in what proportion each item contributes to the cost of giving telephone service. The following extracts from the *Telegraph and Telephone Journal* for August 1918, vol. 4, p. 149, serve to illustrate this:—

"Exchange System.

"*Expenses.*	Rate per station 1915–16 £ s. d.	1916–17 £ s. d.
Administrative and operating	1 12 7	1 13 7
Maintenance of system	1 12 5	1 14 4
Stationery, printing, etc.	0 0 5	0 1 0
Rents, rates, heat, light, furniture, etc.	0 8 2	0 8 0
Value of engineering stores, supplied for war purposes	0 5 0	1 3 1
Interest	0 15 4	0 13 10
Pension liability	0 9 10	0 9 1
Depreciation	1 14 8	1 15 3
Civil pay of men with the Colours	0 4 3	0 6 7
Adjustment of pension liability—overcharges in four previous years	—	0 2 7
Sale of plant to Hull Corporation	0 0 1	—
Totals	£7 2s. 7d.	£8 2s. 2d."

Capital costs.—Capital cost of plant is affected by improvements in design and manufacturing methods, as well as by the costs of material and labour. In the existing types of manual exchange plant, a high degree of standardization in design and methods of manufacture has been arrived at, and the items are handled in

comparatively large quantities. Everything has been therefore, for some years past, favourable to reducing the cost of production of this type of plant, and little further reduction can be expected in the future. Up to the present, automatic plant has not reached this stage of standardization, and the possibilities of improvements in its design and manufacture will not be exhausted for a considerable number of years; nor have the quantities demanded been sufficient to enable the manufacture to be conducted on modern and economical lines. With this type of plant considerable reduction in cost can therefore be expected during the period we have under review, particularly if conditions permit of manufacture in large quantities. The amount of raw material in a large automatic equipment is not very different from that in a corresponding manual equipment. The difference in cost is chiefly in the form of labour, and so tends to be eliminated by improved methods of quantity production.

Interest and depreciation.—The larger capital cost of automatic equipment subjects this type to a higher charge for interest than manual plant. On account of this, the increase in the rate of interest during the war reacts unfavourably against the automatic.

Although there is as yet no experience of either the physical or economic life of an automatic equipment, the nature of the apparatus and the facility with which worn parts can be replaced without wholesale reconstruction, and, if necessary, the whole equipment rearranged to meet changes in the distribution of the subscribers, permit the legitimate estimate of a longer economic life than for the manual equipment. Experience with automatic equipments has tended so far to confirm this view.

Further it is at least probable that the arguments for improvements in service and reduced expenses now being put forward will result, within the next 15 to 20 years, in a departure from the manual type of plant at present standard. If this takes place, equipments of this type will be replaced before the period now assumed for their economic life has elapsed. The rate at which depreciation is calculated for these equipments should be revised to meet this contingency.

Revenue charges involved in replacing plant.—In considering proposals for any extensive changes in the plant, it is necessary to consider specially costs chargeable to revenue over and above those which can fairly be considered as being met by the normal allowances for depreciation. An estimate is made of the depreciated value of the plant in place and the difference between this and the recovery value is the special revenue charge incurred in making the change.

Owing to the war and the changed conditions resulting from it, the revenue charges involved in making changes in plant now and in the immediate future are lower than they are ever likely to be again. Due to the cessation of construction work during the war, the average age of the whole of the plant is 4 years greater than it would otherwise have been. In a going concern when new construction work and replacements are progressing normally, the average age of the plant tends to remain more or less constant at, say, 8 years. This we may take as the average age of the internal plant in July 1914, and, but for the war, would also be its average age now. Owing to the 4 years' stalemate, however, the average age is now, say, 12 years. With the progress of reconstruction work, the age will fall again to about its normal figure. For instance, in London there is now no public exchange less than 4 to 5 years old, and a number of the largest have practically reached the end of their economic life.

The value of the plant in place, therefore, stands at a lower figure than it is ever likely to reach again.

Looking at the matter from another point of view, it will be seen that the depreciation account, reserve fund or other equivalent, is in a better state to meet replacement charges now than it is ever likely to be again, since 4 to 5 years' contributions have been made to it, but during this time practically no extensive alterations or replacements whatever have been made in the plant.*

The rise which has taken place in the value of materials and labour makes the recovery value of plant very much larger in proportion to its original cost than it was before the war. This again is a favourable situation which is not likely to recur. It applies particularly to replacements in which use can be made of much of the recovered material for new purposes.

Maintenance.—The tendency towards increased costs of labour is certain to have its effect upon maintenance charges. We have learnt, however, during the war that women's labour can be used for routine testing and cleaning to a much greater extent than was previously the practice. Such routine duties form a very large proportion of maintenance work, particularly in automatic exchanges, where routine testing can be carried on during working hours.

It is likely that the rising costs of labour may affect automatic systems adversely in comparison with manual. As Mr. McBerty has emphasized,† however, experience with modern equipments has demonstrated that the maintenance force need hardly be more numerous or more skilful than that required for manual equipments of equal size. This view is confirmed by experience in the exchanges converted to automatic in this country, which we believe are in every case being maintained by the same staff as were employed in the manual equipments. The maintenance labour required in modern automatic equipments rarely exceeds 7 man-hours per line per year. Already experience shows that even with existing equipments a lower standard might be applied with no disadvantages resulting. The nature of automatic equipment is such that defects causing any considerable amount of maintenance attention can be effectively and permanently removed by improvements in design at practically no increase in cost, once experience in and a full appreciation of the conditions causing the defect are available. With future equipments, therefore, it is not too much to expect that the maintenance costs may be reduced even below those of manual exchanges.

Rents and other charges on building.—No one will

* With regard to the large and increasing balance standing to the credit of the depreciation account, see the *Telegraph and Telephone Journal*, August 1918, vol. 4, p. 145, and statements of contributions made and renewals met from depreciation fund on p. 149.

† *Journal I.E.E.*, 1917, vol. 55, p. 290.

deny that the tendency of rents and other charges on existing buildings in our large cities is decidedly upwards. The cost of materials and labour for new buildings has largely increased during the war, and owing to the huge demand it is likely to remain high for several years to come.

This item of expense has therefore suffered a very considerable increase, and no reduction to anything like its previous value seems possible as long as present standards of exchange construction are adhered to. Buildings for manual exchanges are necessarily of a somewhat costly type, however severe the style in which they are designed. This is due to the facts that large spaces, free from columns and other obstructions and of a certain minimum width, are necessary for the switch-rooms, and on account of the numerous employees, liberal provision has to be made for lavatory and cloak-room accommodation and for fire exits. With the rising demand for higher standards of comfort, it is probable that provision for the staff will be even more expensive in future than at present.

With a departure from the manual type of exchange equipment relief from these conditions is at once obtained. The architect is no longer restricted to a certain minimum roof span, or to rooms of a rectangular shape, and generally he can design the building in the most economical way without special regard to its particular purpose. During the period of transition, a small amount of manual equipment will probably require accommodation, but after its recovery the floor space made available could readily be let as offices. Extravagant claims made in the past have led to the idea that an automatic equipment can be installed in any building. Possibly it can, but the authors would be far from recommending such a practice. The space available should at least be such that the equipment can be arranged in the most suitable way for economical maintenance, and preferably should be all on one floor. Good lighting is essential, but it need not necessarily be natural lighting. Ventilation without risk of dust or damp is necessary. What can be claimed for the automatic with perfect fairness is that it needs a very much smaller personnel, less floor space, and that it is much more flexible in the arrangement of the equipment and in provision for extensions without interference with existing equipment. It is therefore far less exacting with respect to its housing than equipment of the manual type.

Administrative and operating charges.—During the last 10 years operating charges have risen by more than 150 per cent. The average cost of operating a position in a London exchange, which was about £85 per year in 1908 (including reliefs, supervision and administrative charges), is now, the authors estimate, about £220 per year. This is a truly enormous increase on a very important item of expense. At present, of course, war allowances paid to operators, amounting to 18s. per week, help to inflate the figure. As to the prospects of a reduction, opinions differ considerably. If we assume that only half the war allowances can properly be considered as permanent, the £220 becomes about £170 representing an increase of 100 per cent on the figures for 1908. As has been mentioned in the first part of the paper, all the tendencies are against a decrease. The new fields open to women's labour, the attention now being paid to monotonous and nerve-straining classes of work, the tendency to reduce the number of working hours, and the increasing difficulties of split duties and night work, are all likely to result in operating expenses higher even than the present figures. Further, the qualifications demanded of an operator and the knowledge and skill which she must acquire through a course of training already expensive, are not likely to be diminished with the increasing complexity of large telephone systems. At the same time, with the ever-increasing volume of traffic, her individuality must become more and more suppressed and the nature of the work less and less interesting and attractive to intelligent girls.

In what direction can relief from this situation be sought? Obviously, only by reducing the amount of operating labour per call. The feature of operating in all large cities is the high percentage of calls which require the services of more than one operator. About 80 per cent of all the calls originated in London are, so to speak, operated twice over in this way. An attractive scheme is to eliminate the second or "B" operator, substituting mechanical switching for this part of the work. The "B" operators form about 24 per cent of the total operating staff, so that without making some other reductions in operating labour the relief effected is insufficient. Most semi-automatic systems, however, in addition to eliminating "B" operating, also reduce the time and effort consumed in "A" operating, partly by providing uniform operating on both local and junction calls, and partly by diminishing the physical exertion required. Instead of an average busy-hour load (in large cities) of about 100 to 110 calls per "A" operator, a load of some 300 calls can be handled, so that only one-third the number of "A" operators is required, with a correspondingly reduced number of supervising staff. The result would be a reduction of the total operating staff in large exchanges to about 34 per cent of its present numbers.

Full automatic working offers the possibility of effecting yet a further reduction in staff and operating expenses. With a system in which calls between all subscribers within the telephone area are completed automatically, the only operators needed would be those required for clerical, inquiry, and record duties, amounting to about 12 per cent of the present numbers. By concentration of these duties and the elimination of ticket recording, this number might be further reduced to 6 or 7 per cent of the present operating staff. In all these comparisons the operators employed in the trunk exchange are omitted.

Any figures of this kind raise at once the question of finding employment for the displaced staff. The authors estimate the present operating staff in London at close on 4,000, of which only about 500 would find employment in a full automatic system. When it is remembered, however, that the conversion of the system must extend over at least 7 or 8 years, during which a large manual operating staff would be required, and further that the average length of service of an operator is only 4 years, the difficulty disappears.

Those operators who have taken up telephone work seriously as a career would ultimately find ample employment in the higher forms of operating in trunk exchanges, on inquiry and complaint work, and in private branch exchanges. The latter field alone will continue to afford congenial employment for large numbers of operators. The work is varied and interesting, and whatever developments may take place in mechanical operation for main public exchanges and for inter-departmental connections on private exchanges, it is extremely unlikely that the operator will ever be dispensed with for handling exchange traffic on private branch exchanges. The private branch exchange operator should be towards the public exchange service just what a well-trained commissionaire is to the office. Just as the latter answers inquiries, arranges for interviews, and directs callers to the various rooms and officials, so also the private branch exchange operator answers the calls, obtains the necessary information, and connects the calling party to the correct department. Calls to a private branch exchange are often made for officials by name rather than by the extension number, and in many cases even the name of the official or department required is unknown to the caller who can only state the nature of the business which he wishes to discuss. The completion of such calls demands an intelligent operator thoroughly conversant with the organization of the establishment.

In addition to her duty of completing incoming connections, the operator should be the information bureau of the private branch exchange system, and all inquiries for telephone numbers or other directory information should be made to her. Highly paid officials then avoid wasting time in hunting for telephone numbers and in waiting for the connections to be completed. Further, only one telephone directory is required and the use of old issues is eliminated. If public exchange numbers are called up direct from the extension instruments, a directory for the whole exchange area must be provided at every instrument. If incoming calls are to be completed without the operator at the private branch exchange, callers must be aware of the extension number required. Any proposal to give this information in the directory is almost unthinkable in view of the difficulty in keeping it up to date. The completion of trunk calls to extensions practically demands the services of an operator at the private branch exchange. The objection of operating expense is to a large extent negatived by the saving effected in the time of the officials and staff. Even now it is the practice of all users whose time is valuable to tell off a junior to see the connection through and acquaint his superior only when the wanted party is waiting. Surely it is and will always remain more efficient and economical to concentrate such work and employ an expert to carry it out, in other words, to employ a private branch exchange operator for exchange traffic. But on the other hand to load up this operator with the work of making internal connections between extensions is to waste her time and to affect adversely the exchange service. Such connections are far better dealt with on an automatic system, the difficulties of directories, trunk calls, etc., referred to above, do not apply to them.

Summary.—The war and changes in social conditions of recent years have brought about increases in expenses on every side. The authors have tried to consider what alterations in the methods and plant of the telephone service of large cities might be made to enable us to face these changed conditions. They find that nearly every indication is in favour of the extensive application of mechanical operation. Although the prices of automatic equipment have been subject to the same rise as all other manufactured products, there are possibilities of considerable reductions, due to improved design and manufacturing methods, when the quantities to be handled become more reasonable from the manufacturer's point of view than they have been in the past.

Referring to the Table on page 167, the introduction of a full automatic system would very considerably reduce the administrative and operating charges which form about 23 per cent of the expenses per station and show tendencies to increase out of all bounds in the future. Sufficient experience is now available to show that it would effect very little, if any, increase in the maintenance costs, which form another 23 per cent. A reduction of rents and other building charges would result. The item "interest," amounting to 11 per cent, would show a slight increase, but it must be remembered that the figures on page 167 refer to the whole system, and a large proportion of the interest refers to the line plant. Depreciation (24 per cent) would tend to be increased, assuming the same life for automatic equipments as for manual, but there are reasonable grounds for taking a somewhat longer life than has been the practice for manual exchanges, while with manual equipment a shorter economic life should be used in future on account of the possibility of the force of circumstances compelling their replacement.

The authors think that the position is fairly stated when they say that to proceed in the future with automatic equipment will result in expenses lower than with manual equipment and will afford relief from the upward tendencies of the several important items of expenses. Certainly, if the change is to be made, there is likely to be no more favourable opportunity than the present. They realize that a claim of this nature should be based on careful comparisons of the costs of both systems, but, as explained at the commencement of this section, under the present conditions detailed comparisons would be more likely to provide mere "bones of contention" than to prove any useful contributions to the discussion. A useful sidelight may be thrown upon the question, however, by the following short calculation. Taking the average number of lines on a position in a city exchange as 70, the annual cost of the "A" operator per line at present is £220 ÷ 70 = £3 1s. Thus, to eliminate the "A" operator alone, and retaining the "B" operators just as at present, would warrant the expenditure of, say, £30 per line in mechanical devices.

General Consideration of the Application of Mechanical Operation to Telephone Systems in Large Cities.

The above consideration of the possibilities of improving the service points to the introduction of mechanical operation as the only means of effecting any marked improvements; and the examination of methods by which the upward tendency of expenses may be resisted, indicates the same measure as the best remedy.

The question now arises: To what extent shall mechanical operation be applied? Shall we retain the "A" operator, acting under the telephoned directions of the subscriber as an intermediary between him and the system of mechanism which is to connect him with his correspondent, or shall we provide each subscriber with a dial and give him direct access to the system? In other words, is the "semi-automatic" or the "full automatic" system to be preferred for telephone service in large cities?

Opinions on the question have differed considerably. On the one side there are those who consider that the modern development of the telephone system is such that full advantage can and should be taken of the quicker service and reduced expenses afforded by the "full automatic." On the other, there are many who fear that any proposals to dispense with the personal attention of the operator will have an adverse effect on the service.

The experience and the well-founded records of the performance of the full automatic systems which have now been working in this country for some years, show that control by the operator is unnecessary, except in such special classes of calls as those for trunk connections and those from coin boxes. Even the latter could be handled automatically if suitable methods of charging for the calls were adopted.

The work of the operator is very considerably facilitated by the semi-automatic apparatus, but its monotony is even greater than with the manual system. In fact, it becomes as nearly mechanical in nature as it is possible to make it.

The additional capital cost of the subscribers' dials with the automatic system is almost balanced by that of the operators' equipment and impulse-sending devices with the semi-automatic system, while the latter must be debited with the greater floor space for plant and operators' accommodation, and with the greater administrative and operating charges.

The speed of the service afforded by the full automatic system is undoubtedly greater than that on the semi-automatic. In cases where a direct comparison has been made to ascertain the subscriber's attitude to the question, the result has shown a decided preference for the "full automatic." * The subscriber is evidently quite willing to undertake the dialling rather than await the attention of an operator, even with the speed with which the semi-automatic apparatus endows her.

Experience shows, therefore, that we may expect with confidence that the advantages of the full automatic system can be realized in practice, and that the adverse effect upon the service feared by the advocates of the semi-automatic will not be felt.

It remains to be examined whether there are any insuperable difficulties in the application of full automatic to large cities.

There is in the semi-automatic system a feature which appears attractive for the transition period, namely, that the existing exchange names and numbers may be retained, the operator, with the aid of her controlling machinery, converting these names and numbers into the impulse trains required for the switching mechanism. Special keys are provided, one for each exchange, the depression of which causes the impulses directing the connection to that exchange to be sent. With an extensive area, the number of these keys becomes excessive. For London, even at present, over 100 keys would be required on each position and, at the ultimate, possibly 200 to 300, assuming only four digit numbers were used. It would be necessary for the operator to know the codes for all exchanges and to select correctly the key corresponding to the exchange required. The present difficulties in accommodating and operating order-wire keys are sufficient to condemn any proposal of this nature. Of course, this difficulty could be avoided by adopting the automatic numbering scheme for the semi-automatic system, but this eliminates the very feature the attractiveness of which led us to discuss the question. Even if adopted for the early stages of the conversion with a view to avoiding number changes, the changes would have to be faced on the later conversion to full automatic, and they would then be a much more serious matter on account of the largely increased number of subscribers.

Technical Problems of Automatic Systems in Large Cities.

It cannot be denied that the application of mechanical operation to large cities in which a complex system of manual exchanges already exists, presents very considerable engineering difficulties. The case of London is that which always springs to mind as the one in which these difficulties are more serious than in any other city in the world. The London telephone area extends over 640 square miles, and the density of its development ranges from one or two stations per square mile on some parts of its periphery to about 5,000 per square mile in the centre. It is served at present by over 70 exchanges, with equipment varying from No. 1 central battery switchboards with the most recent improvements, to magneto boards of an almost obsolete type. In spite of its extent it is one organic whole. The intercourse between each part of it and the remainder is such that any attempt to divide it into two or more distinct areas fails on account of the impossibility of choosing a boundary across which the amount of intercommunication could be satisfactorily handled by the methods usually employed between separate areas.

On account of these facts, London may be expected to present every type of difficulty likely to be met

* Relazione della Commissione di Sorveglianza; Rome, 1915, p. 9.

in the application of mechanical operation, and it is for this reason that we have chosen it as an example.

In January 1916 the number of direct exchange lines in the London area was about 147,300. Allowing for increase in the population within the area, and assuming a development up to a figure of 10 for the inhabitants per telephone, it will be seen that the number of stations will ultimately not be far short of one million, with a corresponding number of direct ultimate conditions. It could give a passable service only at an enormous expense.

The map reproduced from the London Telephone Directory in Fig. 1 shows the distribution of the lines over the different exchanges in January 1916. In Fig. 2 the areas corresponding to each of the numbers of lines shown in Fig. 1 have been roughly sketched in, and a proportionate increase in these numbers up to the ultimate development of 700,000 lines has been assumed. The actual development will, of course,

FIG. 1.—London telephone area, showing number of subscribers' lines on each exchange at January 1916. (Total No. of lines 147,330.)

lines of 700,000. The average number of lines per exchange at present is roughly 2,000. The size of a manual exchange is limited by the length of the operator's arm and minimum diameter practicable for the connecting plugs to about 10,000 working lines. On the manual system therefore, some 150 to 200 exchanges would be ultimately necessary. Even with the number of exchanges existing the difficulties of junction wiring are severely felt in their effect both on the service and on the expense. It becomes, indeed, questionable whether a purely manual system would be capable of dealing satisfactorily with the deviate very widely from this simple assumption, and in a way which it is quite impossible to predict without a greater knowledge of the details than the authors possess. Let us assume, however, that Fig. 2 represents the result of an accurate development study made by the administration. Fig. 3 shows a mid-way stage at which the total development has reached 400,000 lines, corresponding roughly to 560,000 telephones. Early in the war it was estimated that the number of telephones in the London area would reach 450,000 in 1922 and 680,000 in 1929.* Interpolating

* *Telephone and Telegraph Journal*, 1915, vol. 1, p. 196.

for our figure of 560,000 and allowing for the 4 years' stalemate, we may estimate that the conditions shown in Fig. 3 will be reached about 1930. Fig. 3 represents, then, roughly the conditions shortly after the conversion of the system might be expected to be complete.

The first step in the application of a mechanical switching scheme of any type is to decide how the numbers by which the subscribers are to be identified, or the combinations of trains of impulses by which they are to be reached, are to be allocated to the different

the reason given being that it leads to confusion and errors on the part of both subscribers and operators. This has often been discussed as one of the difficulties in a full automatic system for London. Whether there is any evidence to warrant these anticipations of trouble the authors do not know. Possibly the real reason for these statements is that it is not practicable to work more than 10,000 lines on an exchange of the standard manual type. Certainly, there is no reason obvious at first sight why an exchange name

FIG. 2.—London telephone area, showing number of subscribers' lines in each area when total development reaches 700,000 lines.

geographical divisions. Unless we use more than 10 different figures or symbols in making up our numbers, combinations of at least six are required in order to form the 700,000 different numbers needed. In other words, we must employ a six-figure or one-million system for the subscribers' numbers, no matter what systems we use for the impulses controlling the switches, whether decimal or non-decimal. It has been an accepted principle in manual practice that the use of more than the exchange name and four digits to identify a subscriber's line is not permissible,

and five digits, e.g. North 23432, should be entirely unworkable while an exchange name and four digits, e.g. North 2343, is common practice. It is clear, of course, that we can use an exchange name or a letter as the first symbol of our six-digit number instead of a figure, provided we mark both sets of symbols on the dial. The use of the letter has been common on American automatic systems, but the authors prefer an exchange or rather a regional name. Our reason is that there is then some association between the telephone number and the geographical position of

the subscriber's premises, which assists memory and checks mistakes. No one would dial "Kent" for "Harrod's Stores," nor "Piccadilly" for "Tilbury Docks," but one might more easily by a slip of the memory dial "B" when one should dial "D."

Since we have the choice of 10 symbols, we can in the first place divide our development map into any number of "regions" up to 10. But just as the lines in a manual exchange area must not exceed 10,000, so the number in each of these regions must not exceed the division shown is the best that can be made, nor that the names are the most suitable. They are concerned only with sketching a rough outline of a possible scheme, with the object of discovering and discussing the main difficulties. It will be noticed that in the outer districts numbers have been assigned very much on the basis of the existing exchange areas, for in these districts the distribution of the subscribers and the arrangement of the line plant will tend to cause these areas to be retained unaltered. In the congested

FIG. 3.—London telephone area, showing number of subscribers' lines in each area when total development reaches 400,000 lines.

100,000. The desirability of avoiding numbers like "Bank 03123" further limits the number permissible in each region to 90,000. As will appear later, use may be made of numbers with 0 in the second place for service lines.

Fig. 4 shows London divided into nine such regions, with the names which might be assigned to each region and the numbers which might be reserved for the lines in each part of the region. The boundaries of these regions need to be determined by an accurate study of the conditions. The authors do not claim that central districts certain re-arrangements have been made, partly because the boundaries of the existing exchange areas do not serve well as the dividing lines between the proposed new 90,000-line regions. It is hardly to be expected that a change in system could be made without some re-arrangement in exchange areas. The process of development up to the 700,000-line date would naturally involve some adjustment of boundaries. With a manual system, of course, such an adjustment, involving change of subscribers' numbers, is made each time a new exchange is opened.

Fig. 4 also shows the marking of the dial corresponding to the numbering scheme assumed.

In Fig. 5 we have indicated the ranges over which the numbers might extend at the date when 400,000 lines are reached, corresponding to some slight rearrangements to the distribution shown in Fig. 3. This is important, for we have assumed that it represents roughly the state of affairs when the conversion is complete. It is therefore the aim which has to be kept in view when discussing the problems of the transition period.

Figs. 4 and 5 are to be considered as representing solely the way in which telephone numbers might be allocated to different geographical parts. The determination of the number, size and position of the exchanges, is quite a distinct matter. We might, for instance, install all the exchange apparatus in one large central exchange or, since there are no expenses for "B" operating, divide it up among several hundreds of small exchanges, without affecting the numbering scheme.

In order, however, to have a concrete case with which to make clear the relations between the various exchanges, let us assume for the moment that any automatic exchanges we establish are to be installed in the same positions as the existing exchanges.

When we have clear ideas of these relations and the arrangements of the junctions between the exchange it will be time to discuss how their number, size and position should be determined. We will take the region we have named "South" for more detailed discussion, since it seems likely to be the most awkward to handle.

The table on page 177 shows the numbering we have

Fig. 4.—London telephone area numbering for full automatic working at the ultimate of 700,000 lines.

assigned to the different exchange areas in "South" corresponding to Fig. 4.

Let us consider in the first place how the traffic originating in the "South" region will be completed. Part of it will be completed within the region, but the greater part will go out to the central districts of London.

Assume for the moment that all the lines in "South" are connected to one exchange, located say in Battersea, and the lines in all the other regions are similarly treated, being connected to a single exchange in each region. Fig. 6 indicates roughly these conditions. A calling subscriber's line would be directed by the concentrating switches (pre-selectors or their equivalent) to a free first selector switch in Battersea, as indicated in Fig. 7. On the levels of this first selector groups of junctions are multipled; each level corresponds to one of the regions and, by directing the wipers of the switch to a particular level, the calling subscriber can extend his connection over a junction into any desired region. For instance, by dialling "2" he obtains access to the junctions multipled on level "2" and extends his call to the exchange in the "City" region. The junctions terminate here in second selectors which respond to the second figure dialled and so on. The lines multipled on the level corresponding to the "South" region (level 8) ter-

FIG. 5.—London telephone area numbering for full automatic working at a development of 400,000 lines.

minate in second selectors in Battersea itself, as shown in Fig. 7, where a call completed within "South" is shown. "South 35764" has called "South 31230." By dialling "South" he obtains a link from the multiple of the first selectors to a second selector in the same exchange. Dialling "3" causes the second selector to extend the connection to a third selector in the 30000–31999 group, "1" causes the third selector to extend it to a fourth selector in the 31000–31999

group, " 2 " causes the fourth selector to extend it to a " final selector " in the 31200–31299 group, " 3 " sets the final selector opposite the level on which lines 31230–9 are multipled, and " 0 " sets it on line 31230.

SOUTH (8).

	Assumed ultimate lines	Numbering
Battersea	9,100	South 10000–19999
Putney	9,900	20000–29999
Croydon	10,000	30000–39999
Richmond	8,450	40000–49999
Streatham	9,700	50000–59999
Kingston	9,550	60000–69999
Wimbledon	7,680	70000–77999
Esher..	1,420	78000–79999
Purley	4,220	80000–84999
Merstham	422	85000–85999
Reigate	1,500	86000–87999
Redhill	1,630	88000–89999
Sutton	5,400	90000–95999
Epsom	1,950	96000–97999
Burgh Heath ..	1,185	98000–99999
	82,107	

Had the call been for " City 31230," the first selector would have extended the connection over level 2 to to a second selector in " City." The action of this

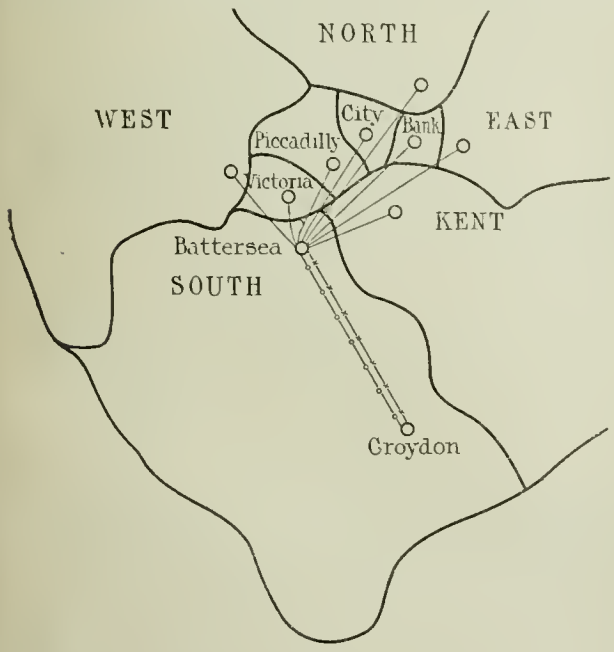

FIG. 6.

—o—o—o— Junctions from concentrating switch to first selectors.
—×—×—×— Junctions from third selector multiple to fourth selectors.

second and the subsequent selectors in extending the connection to " 31230 " would be exactly similar to that described for " South."

A simple arrangement such as that partly shown in Fig. 6, in which each of the nine regional exchanges has lines from its first selector multiple terminating in second selectors in the other eight exchanges, and lines from the particular level corresponding to its own region terminating in second selectors in itself, would provide for the completion of all the traffic originated in each region, both outgoing and local

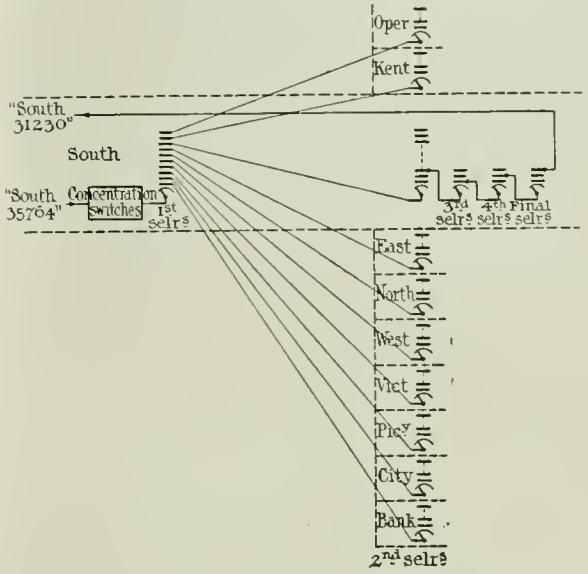

FIG. 7.

to the region. All the junctions would be lines between first selector multiples and second selector switches.

This simple scheme is, of course, totally uneconomical ; we cannot bring lines from Croydon, for example, direct into an exchange at Battersea. We must arrange for calls originated at Croydon to be completed over junction lines in order to reduce the circuit mileage

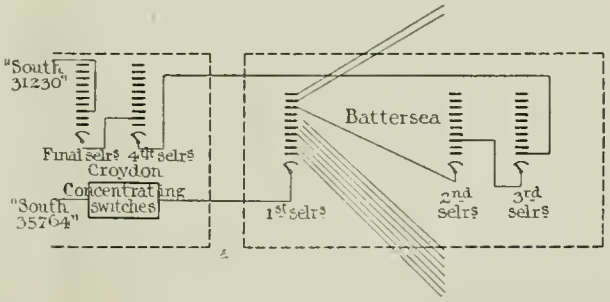

FIG. 8.

of the subscribers' lines to an economical figure. One way of doing this is shown in Fig. 8. We can install concentrating switches at Croydon for the Croydon calls, together with the final selectors, fourth selectors and, perhaps, even the third selectors, through which access to the Croydon numbers (" South " 30000–39999) is obtained. The circuits then required between Croydon and Battersea would be reduced to two groups of junctions, one sufficient for the total traffic originated by Croydon subscribers, and the other sufficient for

the total traffic incoming to them (including calls from one Croydon subscriber to another).

Even with this arrangement applied to all the exchanges in the region, we have not reached a very practical scheme. Battersea has become what is usually called in "automatic" literature a "main exchange," and every connection originated in the South region, whether local or outgoing, and also every connection incoming to the South region, is completed through Battersea. It is obviously bad for transmission and extravagant in circuit mileage on the junctions to engage a circuit from Croydon to Battersea and another from Battersea to Sutton, for every call between Croydon and Sutton, or two circuits between Croydon and Battersea for every call between two subscribers on Croydon. The arrangement has many other disadvantages. If Battersea exchange were put out of commission by fire or accident the whole South region would be deprived of service. Administration too would be very cumbersome, if very distant exchanges like Battersea were involved in and responsible for traffic between neighbouring exchanges like Redhill and Reigate.

This is the second difficulty that has been feared in the application of automatic working. It is easily surmounted or, rather, in reality, it does not exist. Fear of it has arisen from a lack of comprehension of the junction arrangements of which an automatic system is capable.

The need for carrying the whole of the traffic originating in South through Battersea arises from the fact that Battersea is the only exchange which we have provided with first selectors. If we put first selectors in Croydon and provide junctions from the multiple on these selectors to second selectors in each of the regional exchanges, Croydon subscribers can complete their connections to other regions without passing through Battersea. This is indicated in Fig. 9. Level 8 on these first selectors, corresponding to the South region, will have links to second selectors in Croydon exchange itself, and these second selectors will have access to third selectors, etc., also in Croydon. Now if our Croydon subscriber "South 35764" calls another Croydon subscriber "South 31230," the connection can be completed entirely within the Croydon exchange. By dialling "South" he obtains a link from the multiple of the first selectors to a second selector also in Croydon. Dialling "3" causes the second selector to extend the connection to a third selector in the 30000–30999 group, "1" causes the third selector to extend it to a fourth selector in the 31000–31099 groups, and so on as before.

Suppose now our Croydon subscriber "South 35764" requires a subscriber at Sutton. The subscribers at Sutton have numbers "South 90000" to "95999." Dialling "South" selects a link from the home level (level 8) on the first selectors to a second selector in Croydon exchange as before. Dialling "9" causes this second selector to choose a line from level 0 on the second selector multiple. This line is a junction terminating in a third selector in Sutton, which will extend the connection through fourth and final selectors to the subscriber required (see Fig. 9).

The whole of the numbers commencing with "South 9," however, are not in the Sutton area; some ("South 96000" to "97999") are in the Epsom area and some ("South 98000" to "99999") in the Burgh Heath area. Suppose our Croydon subscriber "South 35764" requires one of these, say "South 98230." We have seen that dialling "South"—"9" extends the connection to a third selector in Sutton. Levels 0 to 5 on this selector are home levels having links to fourth selectors in Sutton. The lines from levels 8 and 9, however, are junction lines terminating in fourth selectors in Epsom, which, responding to the dialling of "2," extend the connection to final selectors in the "South 98200–98299" group of Epsom lines.

Referring to the table showing the numbering, it will be seen that level 1 on the second selectors provides

FIG. 9.—Showing how traffic originated in Croydon is completed.

junctions to Battersea, level 2 to Putney, level 4 to Richmond, and so on. Level 3 is the home level and has links to third selectors in Croydon itself.

With the arrangements sketched in Fig. 9 we can, then, complete all the calls originated in Croydon for other subscribers in the "South" region, only carrying them through Battersea when Battersea subscribers are wanted. Similarly, we can complete all Croydon's traffic to regions other than "South" by direct junctions to their regional exchanges. Junctions to these regions are multipled on the first selectors at Croydon, and terminate on second selectors in the regional exchanges; junctions to other exchanges in the same region are multipled on the second selectors and terminate on third selectors in the other "South" exchanges.

As an example of a slightly modified nature, let us

take the traffic originated on Esher, which we assume is too small to warrant direct junctions to each region. It is therefore not provided with first selectors. Its concentrating switches extend calls to first selectors in Kingston exchange as shown in Fig. 10. From the first selectors in Kingston, which is equipped similarly to Croydon, junctions are provided to regions other than South. From the home level on the first selectors (level 8) second selectors in Kingston are reached and, from the multiple on these, other exchanges in "South" are accessible. In this way the outgoing traffic from Esher is provided for. Its local traffic also makes use of the first and second selectors in Kingston and, since its numbers commence with "South 7" in common with Wimbledon numbers, the second selector is directed to the home level (level 7) and extends the connection to a third selector in Wimbledon exchange. Since Esher numbers lie between "South 78000" and "79999" the third selector is directed to level 8 or 9, and extends the connection over a junction to a fourth selector in Esher exchange, which completes it via a final selector. Esher exchange therefore has concentrating switches and fourth and final selectors only. It completes its outgoing traffic via Kingston and its local traffic via Kingston and Wimbledon.

This method of dealing with the local traffic compares unfavourably with manual practice. It must, however, be remembered that only about 36 per cent of Esher's traffic is local and that, although it is routed through two exchanges, this involves no expenses for "B" operators as with manual lending junction working. It would be better if Esher subscribers could have been given numbers commencing with "South 6" instead of "South 7." They would then have been reached via Kingston, and local traffic between Esher subscribers would have been completed over shorter junctions from Kingston to Esher instead of junctions from Wimbledon to Esher. But owing to the assumed size of Kingston approaching 10,000 at the ultimate, Kingston numbers are not available. The difficulty could be avoided by an adjustment of the exchange areas by throwing some 1,700 Kingston lines on to Wimbledon and so relieving Kingston sufficiently to leave numbers "South 68,000" to "69,999" instead of "South 78,000" to "78,999" for Esher. Should it be uneconomical to take these 1,700 lines direct into Kingston, a sub-exchange similar to Esher could be established for them working into Wimbledon. The annual costs of the different schemes should of course be compared and the most economical method chosen. The authors do not wish to be understood as recommending in any way the particular arrangement that has been discussed. They have followed the assumed existing exchange areas and have discussed the difficulty which has arisen from this with a view to seeing how it might be overcome.

It should be stated in passing that arrangements by which the engagement on local calls of two junctions to the nearest exchange with first selectors can be avoided, have been developed. The junction outgoing to the first selectors is engaged temporarily until the impulses sent in determine that the call is to be reverted to the sub-exchange, when both junctions are freed and the switches on which they terminate released. These arrangements are necessarily somewhat complicated and are not to be recommended unless their use is clearly demanded on economical grounds.

Summarizing briefly the arrangements shown in Figs. 9 and 10 for completing calls originating in the "South" region, we have first selectors provided in certain exchanges—Battersea, Croydon, Purley, Putney, Kingston, Richmond, Streatham, Sutton, and Wimbledon. From the multiple of these first selectors, direct junctions terminating in second selectors are provided to other regions. From the home level on these first selectors, links are taken to second selectors in the same exchange. The multiple on these selectors carries

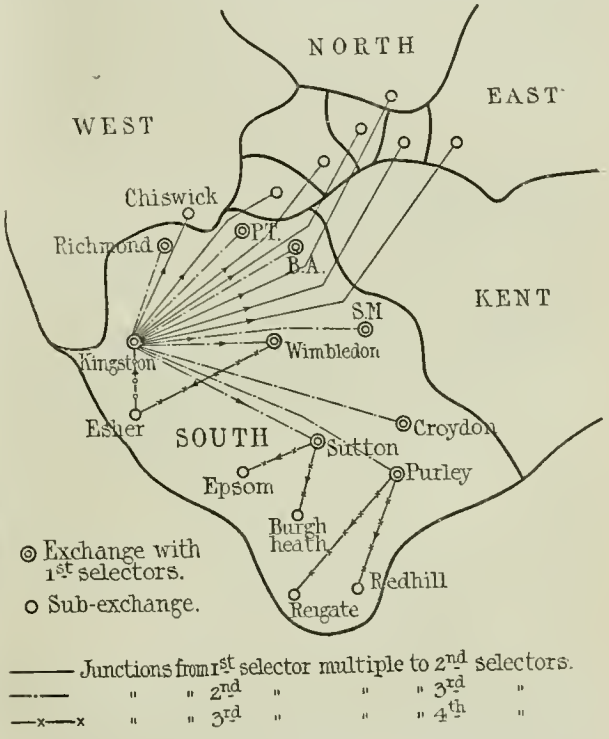

FIG. 10.—Showing how traffic originated in Esher is completed.

junctions terminating in third selectors in the other exchanges in the list above, except on the home levels which carry links terminating in third selectors in the same exchange or in sub-exchanges.

From first selector levels there are, then, groups of junctions radiating to the different regions, and on the second selector levels a system of intra-regional junctions connecting the exchanges of that region, such as is sketched for the "South" region in Fig. 11. In addition, there may be junctions outgoing from concentrating switches in sub-exchanges to first selectors in the nearest exchange, and incoming junctions to third or fourth selectors in sub-exchanges from the exchange with which the sub-exchange has numbers in common.

Let us turn now to the question of completing the

traffic incoming to the "South" region from other parts of London, considering particularly the case of our Croydon subscriber "South 35764." His incoming calls (except trunk calls) come from all parts of the London area, but chiefly from the central districts. All of them are originated on regional systems similar to that which we have described for "South." By dialling the name of the region required, namely, "South," the calling subscriber has directed a first selector to level 8 on its multiple, where it finds a junction to the "South" region terminating in a second selector, let us say, in Battersea exchange. By dialling "3" this second selector is directed to the level providing junctions to Croydon where they terminate in third selectors. These junctions are part of the intra-regional system sketched in Fig. 11, and the call is completed over fourth and final selectors in Croydon. Fig. 12 indicates this arrangement. The description above would apply to, say, a "Victoria" subscriber who had

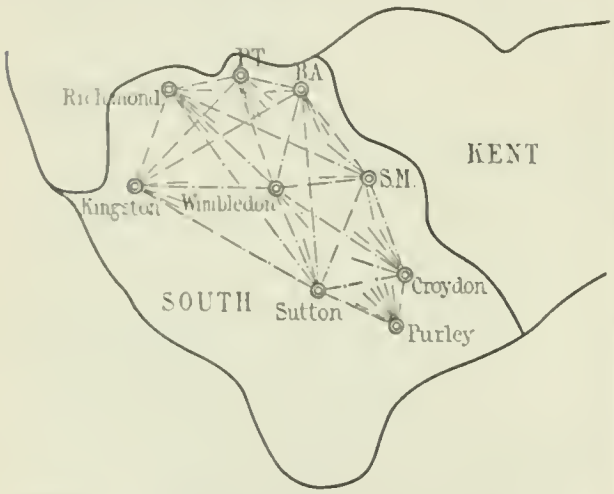

FIG. 11.—Junctions from 2nd selector multiple to 3rd selectors in "South" region.

called "Croydon 35764." All the traffic from the central and eastern districts of London to Croydon would be completed in this way via Battersea, which, as we have said, would be referred to in automatic literature as the main exchange for "South." But is it necessary to carry the connections from districts adjacent to the boundaries of the "South" region through Battersea? For example, must calls originated in Bromley for Croydon go via Battersea?

Here we meet another difficulty which is really non-existent. The "Kent" region would be laid out similarly to "South" with a system of exchanges having first selectors and sub-exchanges dependent upon these. Let us assume that Bromley, Sydenham, Brixton, New Cross, Woolwich, etc., have first selectors the multiple on which carries junctions to the different regions. There is no reason, however, why the second selectors in which the junctions to any one region terminate should all be in the so-called "main" exchange. The system of intra-regional junctions sketched in Fig. 11 is available at any one of the exchanges other than sub-exchanges, so the junctions from level 8 on the first selectors in Bromley which carry calls originated in Bromley for the "South" region can be taken direct to Croydon and not to Battersea. Similarly, Sydenham's "South" junctions can be taken to Streatham, and Chiswick's "South" junctions to Richmond. A connection from Bromley for "South 35764" is extended to a second selector in Croydon and completed via third, fourth, and final selectors also in Croydon. Had it been destined for Esher the second selector in Croydon would have extended it over the intra-regional junction system to Wimbledon and thence to Esher as described on page 170. Fig. 12 indicates how this cross-boundary traffic can be handled. The routing is little, if any, less direct than with manual practice. It is only necessary to enter the "South" region via Battersea when this is desirable, and Battersea, instead

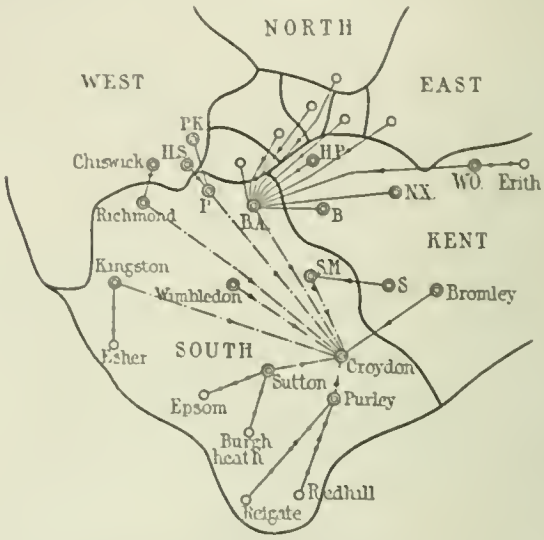

FIG. 12.—Showing routes for traffic incoming to Croydon ("South" 30,000 to 39,999).

of being the "main exchange" for "South," becomes the "main junction centre." Exchanges like Richmond and Putney can be regarded as junction centres for traffic from "West," and Streatham and Croydon as junction centres for traffic from the neighbouring parts of "Kent."

So much for the traffic incoming to our Croydon subscriber from other regions. The traffic originated in the "South" region itself is directed over the home levels of the first selectors, and extended over links to second selectors in the same exchange which provide access to the intra-regional junctions. For example, a call originated on Esher uses a first selector and a second selector at Kingston, and is extended over a Kingston-Croydon junction to a third selector in Croydon as sketched in Fig. 10.

Fig. 13 shows the different routes taken by calls originated in various places. A call from Erith uses a first selector at Woolwich, which extends it over its "South" level to a second selector at Battersea. The second selector extends it over a Battersea-Croydon junction to a third selector in Croydon. A call origin-

ated in " Victoria " is also extended to a second selector in Battersea from whence its route is similar. A call originated in Chiswick is extended by the first selector in Chiswick to a second selector in Richmond, and from thence to a third selector in Croydon. A call from Bromley is extended over the " South " level at Bromley direct to second selectors in Croydon which have access over their home level (level 3) to third selectors, whose multiple is common with that of the third selectors reached from Richmond and Battersea. From the

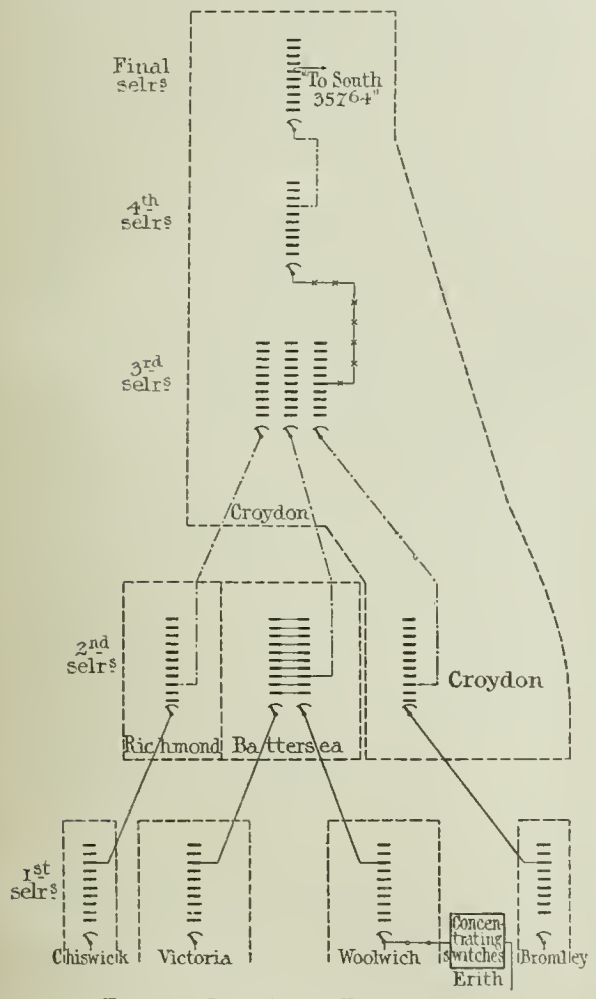

Fig. 13.—Incoming traffic to Croydon.

third selectors onward all calls, of course, follow similar routes.

Arrangements of junctions in Central London.—In densely developed areas like those included in the regions here named Bank, City, Piccadilly, and Victoria, it will be desirable to provide direct junctions between each automatic exchange and every other in order to secure the shortest routes for the large numbers of junctions. The junction arrangements are therefore the same as with the manual system, although the all-powerful factor necessitating direct working, namely, operating costs, is absent in the automatic system. Insurance against interruptions in service and convenience in the organization for the maintenance of junction circuits would also tell in favour of direct junctions.

To provide for direct junctions between all exchanges in these regions, the junctions could be arranged between the second and third selectors. Thus, a subscriber on Avenue would, by pulling " Vict." on the dial operate a first selector in Avenue, which would extend the connection not to a junction into the " Victoria " region, but to one of a group of second selectors installed in Avenue exchange itself. By pulling, say, " 8 " he would direct this second selector to a level on which junctions to the particular exchange required (i.e. Kensington) are multipled. He thus secures a direct line from Avenue to Kensington. Further impulses operate third, fourth, and final selectors in Kensington to select the number called.

Determination of the number, size, and position of exchanges.—In the above illustrations it has been assumed, for the sake of clearness, that the new automatic equipments are installed in the same or very nearly the same locations as the existing manual exchanges. Assumptions have also been made with regard to the types of selectors with which each exchange is equipped, and how its junction circuits would be arranged. These are, of course, matters requiring careful study.

The position of an automatic exchange is determined by very much the same factors as those operating with the manual system, chiefly subscriber's line mileage, and land and building costs. In the suburbs, however, where the telephones are distributed in groups separated by comparatively open districts, the facilities afforded by the automatic system for opening sub-exchanges, without incurring additional costs for " B " operating, would lead to the provision of more exchanges and so would have an influence on their position. For instance, where the denser parts form an area of elongated shape as in Croydon, an exchange towards each end might take the place of a single exchange in the centre.

In densely developed Central London the size of the exchange, no longer limited by the length of the operator's arm, would tend to increase in order to secure the advantages of the reduced cost per line of large buildings. It would, under the ultimate conditions, be limited possibly only by the physical difficulties of providing duct space in the approaches to the exchange building.

The exchanges in the suburban districts would therefore tend to be more numerous, and those in the central districts less numerous, than with a corresponding manual system.

The type of equipment to be employed in each exchange in the suburban districts is also a matter for study from the economical standpoint. Whether an exchange like Richmond (see Figs. 9, 11, and 12) should be equipped with first selectors and have junctions from them into each region, with junctions from its second selectors to Putney, Battersea, Streatham, Wimbledon, Croydon, Sutton, and Kingston, as we have assumed, or whether it should make use of the first selectors in, and junctions from, Putney, would be determined from a comparison of the junction mileage

necessary with each scheme. Yet another alternative would be to provide first selectors in Richmond, multipled with junctions to other regions, and to take the lines from the home or "South" level on these switches to second selectors in Putney. Richmond now, instead of having direct junctions to each other exchange as shown in Fig. 11, makes use of Putney's junctions for its "South" calls.

Problems of the Transition Period.

Change of numbers.—The selection of the method and time for the change of the subscribers' numbers is one of the serious problems to be faced in the introduction of the full automatic system. Seeing how intimately it affects the subscribers, it is a problem which calls for ample consideration in arriving at the best solution, and boldness and firmness in applying the solution decided upon.

The need for the change of numbers is sometimes looked upon as a disadvantage accompanying the introduction of the full automatic system. With a manual system the opening of each new exchange is usually attended by some re-arrangement of exchange areas and consequent re-numbering of subscribers, so that as a manual system develops the need for number changes is always present. With the full automatic system, however, if a well-designed numbering scheme based on careful development studies is applied at the outset, the numbers then allotted need suffer little change thereafter.

The method adopted for the change should in the first place be that which will cause the least inconvenience to the subscribers. It should involve the administration in as little expense as possible for notices, new directories, dealing with inquiry traffic, re-marking multiples, etc. The method and the time should be reasonable from the point of view of the public so that the change gives rise to as little adverse comment as possible. The question of how the change is made has also a considerable bearing on the methods of handling junction traffic.

To change the number of each subscriber as his line is converted from manual to automatic working, appears at first sight most reasonable, but it has many disadvantages, the chief of which are the lengthy period over which number changing is in progress and the uneconomical methods of handling junction traffic which result from the unsuitability of the existing numbers to dial calling

On the other hand, to change the numbers throughout the area at once would result in many numbers, particularly in outlying exchanges, being changed unnecessarily soon For although the addition of a digit to the exchange name and four digits of a City number would be no serious inconvenience, it is not desirable to substitute numbers like "South 88361" for "Redhill 61" as long as the required subscribers' numbers have to be transmitted orally. It is preferable as long as the outlying exchanges retain manual equipment to allow them to retain their present numbering

The authors' proposal would be therefore to change at one time the numbers of all the subscribers connected to exchanges in the "Inner London" area, i.e. within the boundaries of the present County of London. Each "Outer London" exchange would retain its present name and numbering until it became incorporated in the full automatic exchange system. This distinction between "Inner" and "Outer London" would not appear unreasonable to the subscribers, for the dividing line is already marked. "Inner" and "Outer London" subscribers pay different rates and the fees charged to them for junction calls are differently arranged. Since by far the greater amount of the traffic originated in the "Inner" area is completed within that area, a very large proportion of the calls originated in any automatic exchange introduced into the "Inner" area could be dealt with by the dial and only a small percentage would need to be telephoned to an operator. These would be the calls for "Outer London" exchanges on which the numbers remain short and suitable for telephonic transmission.

The proposal to change all "Inner London" exchange names and numbers to the new automatic region names and numbers at one time prior to the commencement of the work of converting the plant, has numerous advantages. The change could be made shortly after the public announcement of the decision to install the automatic system, at a time when the subscribers would be in a mood to accept it willingly. It could be made at a date which might be definitely fixed a considerable time in advance, so that the subscribers have plenty of notice and an opportunity to dispose of stationery, etc., bearing the old number. When number changes are made on the occasion of an exchange transfer, the notice must necessarily be short on account of the delays to which the conversion of plant is exposed. Further, there is the very considerable advantage in changing all the numbers at the same time that each user knows his correspondents' numbers are being changed. When changes are made on the occasion of an exchange transfer, the subscribers involved may be well aware of the change, but other subscribers calling for them are likely to be ignorant of it. This should assist considerably in the reduction of inquiry traffic after the change.

The earlier the change is made the less the inconvenience both to the subscribers and the administration, for, as time goes on, conditions will become more and more settled and subscribers more and more numerous. A wholesale change such as that proposed, not only tends, as shown above, to reduce the actual trouble always attendant on number changes, but is likely to give rise to less irritation and imaginary trouble than a succession of piecemeal changes extending over 8 to 10 years. Uninformed newspaper criticism is likely to consider the latter method a "muddle," whereas any trouble following the universal change is easily explained and soon subsides.

By making a universal change before commencing the conversion, time is given for subscribers to become accustomed to the new numbers and one of the difficulties attending exchange transfers is eliminated.

The introduction of the new numbers throughout a considerable portion of the area makes it possible for subscribers on automatic exchanges to call with the dial on all but a very small proportion of their traffic.

Calls for any exchange on which the existing numbering is retained must necessarily be telephoned to an operator having the same functions as the "A" operator in a manual system. Calls for a manual exchange on which the automatic numbers have been introduced can be dialled, the number required appearing on lamp signals in front of the distant "B" operator, who completes the connection without speaking to the subscriber. In fact, as far as the subscriber is aware, the whole connection might have been set up automatically. Obviously, it is decidedly economical to introduce the new numbering on as many manual exchanges as convenient, at least as soon as, if not before, the first automatic exchange is brought into use.

Since the lines on all "Inner London" exchanges would, after the change, bear numbers commencing with the regional names, subscribers on automatic exchanges would naturally make calls for them with the dial. These calls would be completed by the distant "B" operators as described above. Since the names of "Outer London" exchanges do not appear on the dial, subscribers would be unable to dial them and would call an "A" operator by pulling "O" or any other number assigned for the purpose. Thus, only "Outer London" calls would be handled through "A" operators; this eliminates the difficulty of charging the junction fees on such calls, assuming tariffs remain on the same system as at present. As long as this is the case the "A" operators, through whose agency "Outer London" connections are established, would record by ticket all such calls. If desired, "telephone unit metering" might be introduced in all "Inner London" calls on each automatic exchange as it is brought into use, ticket-recording being retained on "Outer London" calls until the "Outer" area is joined up, section by section, with the main automatic system. As each section is joined up so that calls to it are completed automatically, the proper rate for "telephone unit metering" would take the place of the manual operator's ticket record.

Stages of conversion.—As foreshadowed in the discussion on re-numbering, only the "Inner" (County of London) area would at first form a united automatic exchange system. Any outlying exchanges converted would remain individual centres, retaining their old name and, perhaps even to a large extent, their old numbering, just as Epsom, which has already been converted, does at present. As the network is built outwards to them, they could assume the new numbering and be embodied in the main system.

The first stage in the conversion would be that between the re-numbering of the "Inner London" area and the opening of the first automatic exchange in this area. At some date coinciding with the issue of new directories, all order-wire key and outgoing junction multiple-marking, etc., corresponding to "Inner London" exchanges would be changed to the new codes, and advantage might be taken of the opportunity to effect any minor changes of subscribers' numbers in order to re-arrange exchange areas, or to group private branch exchange numbers, etc. The change of subscribers' numbers would in the great majority of cases be effected by substituting for the present exchange name a regional name and one digit. Thus, "Mayfair 8492" might become "Piccadilly 78492"; "Avenue 9046" might become "Bank 19046"; "Kensington 146" must have the place of the second figure filled in with 0, becoming "Victoria 80146."

It will be noticed that the region name and the additional digit indicate the exchange to which the subscriber is connected.

Thus "Mayfair" is indicated by "Piccadilly 7 and 8."
"Avenue" is indicated by "Bank 1 and 2."
"Kensington" is indicated by "Victoria 8 and 9."

At the time decided upon for renumbering, these new descriptions would be substituted for the existing exchange codes on all order-wire key-tops, outgoing junction designation-labels, etc. A subscriber on "Hop" who wishes to be connected with the line of which the old number was "Mayfair 8492" will ask for "Piccadilly 78492." The operator will depress the order-wire key marked "P$\frac{7}{8}$," which connects her with the order-wire to the Mayfair exchange. She will be assigned and will plug into a junction in a group marked in a similar way. The order-wires and junctions marked "P$\frac{7}{8}$" lead to Paddington, those marked "P$\frac{1}{2}$" lead to Museum.

There may be cases where it is desirable to divide an existing exchange area between two or more areas, and possibly even between two neighbouring regions. We have assumed that it is desirable to follow this course in the case of Avenue exchange. At the ultimate, the present area assumed for Avenue is estimated to contain 33,100 lines. For the sake of example, let us assume that part of the Avenue area containing 13,100 lines will form part of the "East" region, the remaining 20,000 lines remaining in the "Bank" region. Then subscribers in the part to be transferred should be given "East" numbers, although they remain working on the Avenue manual exchange. At the end of the transition period, the number of lines so placed would, assuming proportional development, amount to about 8,000 lines. These lines would be allotted the prefix "East 2." The digit "2" would not be used in connection with any of the other exchanges in the "East" region. The present "East" exchange would be reached over junctions, etc., marked "E1." Other exchanges in the "East" region are "Outer London" exchanges, and would retain their present names and numbers until their conversion took place. The remaining lines in the western half of the Avenue area amounting to 20,000 at the ultimate and about 11,500 at the end of the transition period, would be given numbers commencing with "Bank 1" or "Bank 2." The present Avenue exchange, as long as it remains manual, would be reached therefore by order-wires and junctions marked "E2," and also by those marked "B$\frac{1}{2}$." For example, "Avenue 9046" might become "Bank 19046," while "Avenue 9047" might become "East 29047." The operator at, say, Hop on being asked for the former subscriber would depress the order-wire key marked "B$\frac{1}{2}$"; if asked for the latter, she would choose that marked "E2." Both of these would lead to Avenue exchange. In fact, the two keys might be joined up to the same order-wire, and

the one group of junctions might bear both markings and be numbered consecutively throughout the group. Fig. 14 illustrates this.

Similar arrangements may be made in every case where the new region boundaries do not coincide with the old exchange area boundaries. All that is necessary is to see that a separate digit is available for use as a prefix to the numbers of those lines which are to be transferred.

The illustrations given above will serve to show how the working of the existing manual system would continue during the period after the re-numbering. The next stage would be that of the gradual conversion of the plant, which might commence as soon as the subscribers and staff had become familiar with the new numbering. Conversion would proceed in the order defined by the need for replacement of worn-out equipment, demand for increased accommodation, and other factors. In some cases, existing equipments might be replaced by new automatic plant in the same buildings; in others, new buildings might be erected to receive it, new exchange areas being formed out of several old areas. In fact, all the construction and reconstruction work incidental to the growth and renewal of a telephone plant could proceed as usual, with the exception that the exchange plant installed would be of the automatic type.

The system during this stage would comprise:—

(a) "Inner London" exchanges with the existing manual plant.
(b) Existing "Inner London" exchanges converted to automatic working.
(c) New "Inner London" exchanges built with automatic plant.

All the above would be working with the new numbering

(d) "Outer London" exchanges with the existing manual plant.
(e) "Outer London" exchanges which have been converted to automatic working.

As the conversion progresses, the "Inner London" area would gradually become completely automatic. The majority of the outer exchanges would probably remain manual until the latter stages of the conversion, for they are small at present and it would perhaps be economical to extend them and even renew them where necessary with manual plant taken from the displaced "Inner London" equipments.

The problem of the second stage while automatic and manual exchanges exist side by side is, of course, the question of how the junction traffic is to be handled.

Methods of handling junction traffic.—Calls originated on the automatic equipments for lines connected to other automatic equipments forming part of the same system are, of course, dealt with fully automatically in accordance with the ultimate arrangement.

Calls for lines on equipments not yet converted need the assistance of a manual operator for their completion. There is, however, the possibility of installing automatic switches in the manual exchange and multiplying the lines over both manual and automatic sections. This plan has been used in some large American systems, but it is scarcely applicable in London, at any rate in the early stages of the conversion when the manual exchanges are much more numerous than the new automatic exchanges.

The introduction of the automatic numbering scheme in the existing exchanges permits the use of the dial in calling lines on distant manual equipments, the required number appearing on lamp signals in front of the distant "B" operator. This method was illustrated by Mr. McBerty on the model shown by him in connection with his paper on "Machine-switching Telephone Gear" * and named by him the "carriage-call" system. This name conveys very little to British minds, since we are not familiar with this system of calling carriages. We shall allude to it therefore throughout this paper as the "intimator" system. All calls originated by subscribers on automatic equipments for lines on the re-numbered "Inner London" exchanges, would be dealt with by "intimator."

The automatic subscribers would be instructed that when the exchange name of the required line is not one of those appearing on the dial, he should dial "O" for the operator. This would be the case on "Outer London" calls only. Dialling "O" would extend his line to an "A" operator at an outgoing junction switchboard preferably, but not necessarily, in the same building as the automatic equipment. This operator would inquire the number wanted and the number of the subscriber calling, and complete the connection, in the same way as at present, recording it on a ticket so that the junction fee might be charged. Many such calls are completed over junction centres. Should an exchange now serving as a junction centre for this traffic be converted to the automatic system, the manual board used for its manually-operated outgoing traffic would be available to continue the work of the junction centre.

For the incoming traffic to the automatic exchanges from manual equipments, three methods are available:—

(i) The manual operators might be provided with dials or with key-controlled impulse senders. Dialling would impose much too great a load on the operators, particularly towards the end of the transition period when nearly every call would be to an automatic exchange.

(ii) Semi-automatic positions might be installed in connection with the junctions incoming to the automatic exchanges from manual exchanges.

(iii) Manual "B" positions over which the subscribers' lines are multipled might be installed in the automatic exchanges.

On the whole, the balance of advantages seems to be in favour of (iii) for the following reasons. The semi-automatic "B" operator, assigning junctions over an order-wire and setting up the numbers required on keys, can carry a load very little, if any, greater than the manual "B" operator who completes the connection by plugging into a jack, provided that the cord circuits are arranged for automatic (i.e. keyless) ringing. The former method requires the provision of new equipment, desk-shaped positions, key sets, impulse senders, new

* *Journal I.E.E.*, 1917, vol. 55, p. 265.

junction-circuit equipment, etc., and each call engages a series of switches through the automatic equipment. The equipment for the latter method is ready to hand in the shape of the existing " B " positions with their multiple and cord circuits, which would be suitable with very slight modifications for the new service. In some cases it might not be necessary even to move them. The calls are completed direct, so that for some time the full complement of switches would not need to be provided on the automatic equipments. Seeing that as the conversion proceeds more and more of the incoming traffic would be completed automatically, the equipment provided for dealing with it manually would be in use for a comparatively short time. It is preferable therefore, from the economical standpoint, to use the displaced manual sections rather than to purchase new semi-automatic plant.

" Outer London " exchanges remaining manual would obtain connections on automatic exchanges either via junction centres or by direct lines to the " B " switchboards just as they do at present.

Outlying exchanges converted to automatic, and not forming part of the united automatic system, might obtain and receive all junction connections over manual positions just as Epsom does now. Suitably situated exchanges which will ultimately have first selectors with direct junctions into each region, might be given the ultimate numbers at the time of their conversion. Their subscribers could then dial lines on converted " Inner London " exchanges direct, but as their traffic would scarcely warrant intimators at each exchange remaining manual, they would need to call in an operator for other calls. This would entail modifications in the subscribers' instructions from time to time as the distant exchanges were converted. On the whole, therefore, it would probably be more convenient for all junction traffic to and from converted " Outer London " exchanges to be dealt with manually until the main network of the automatic system is extended to them, especially as the manual plant recovered from other exchanges is available for this purpose. Until they are linked up to the main system, such exchanges would retain their present names and practically their present numbering. The dials would carry no region names and the subscriber would be instructed that he could obtain all lines on his own exchange with the dial, but for all other exchanges he must call in the operator. This suits the present tariffs, for junction fees are charged to an " Outer London " subscriber for calls to all exchanges other than his own.

Trunk calls during the transition period would be handed in over the " A " positions and would be completed over the manual " B " positions. In the ultimate arrangement, record operators in the trunk exchange itself might be reached by dialling the number assigned for this purpose, and the connection might be set up over the automatic exchange system from dials or key-controlled impulse senders on the trunk positions.

Conversion of a typical exchange in the " Inner London " area.—In order to illustrate the above discussion of the transition period, let us consider in greater detail the application of the proposals outlined to the conversion of typical exchanges. Assume that we have reached the time when Holborn exchange is about to be converted and that an automatic equipment is in process of installation in a new building.

Holborn, we assume, is a case similar to that shown in Fig. 14 for Avenue. A part of its exchange area is eventually to be included in the " North " region. The lines in this part have been re-numbered with " North " numbers by prefixing, say, " North 2 " to their existing numbers. The numbers of the lines in the remaining part of the area have been prefixed with " City 6," for this part is to be included in the " City " region. The lines retain their present positions in the multiple and no special marking is required. The existing order-wire key-tops and outgoing junction designation labels throughout the London system have been replaced by those bearing the new codes. Order-wire keys and junctions marked " N2 " and also those marked " C6 " both lead to Holborn exchange.

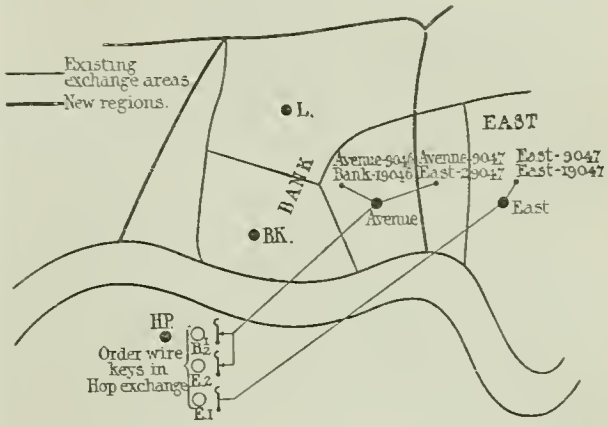

FIG. 14.—Sketch showing re-numbering of an area which is divided between two regions.

On the " B " switchboard at the incoming junction positions corresponding to other exchanges which are already working on the automatic system, intimators have been installed. Subscribers on these exchanges call for Holborn numbers by dialling, say, " North 2 8967 " or " City 6 8968." These two lines, of course, occupy neighbouring jacks on the Holborn multiple. In both cases the call is extended over a junction terminating on an intimator position in Holborn exchange. This might be accomplished by multipling these junctions in the automatic exchanges over the second selector level corresponding to " North 2 " as well as that corresponding to " City 6." Since the impulses corresponding to the region name and those corresponding to the prefixing digit are taken up in the automatic exchange itself, only the remainder of the number appears on the intimator. This, of course, is the Holborn subscriber's old number and corresponds to the position of his jack in the multiple.

In connection with the new automatic equipment, a " B switchboard " has been erected, using sections and equipment recovered from other exchanges, with sufficient positions for the incoming junctions from exchanges remaining manual at the date of the opening. After the transfer, calls from these exchanges for " City

6" or "North 2" subscribers are telephoned over the order-wires to these positions by the "A" operators in the manual exchanges, who pass the call as "8067" or "8068" only. The "B" operator in the automatic exchange thus completes it as in the manual exchange practice. There is no need for her to be troubled with the prefixes; these are omitted by the "A" operator. The "A" operator might be instructed to make a slight pause after the prefix, e.g. "City 6—8068" when repeating the number to the calling subscriber, so dividing it into the part to be looked for on the junction multiple and the part to be spoken over the order-wire.

Calls from automatic exchanges after the transfer reach third selectors in the new automatic exchange. The subscribers originating them dial "City 68068" or "North 28067" just as they did before the transfer, and the trains of impulses following "City 6" or "North 2," instead of controlling the intimator, direct the third, fourth, and final selectors in the new automatic equipment to the required line.

As far as the subscribers on other exchanges, whether manual or automatic, are concerned, the transfer makes no difference. They obtain their connections with Holborn lines by the use of the same numbers and in the same way as when the Holborn equipment was manual.

A subscriber in Holborn exchange itself will be provided with a dial at the time of the transfer. He is instructed that all numbers commencing with a name which appears on the dial can be dialled by him. For all other connections he must dial the operator. Calls for other automatic exchanges in the "Inner" area are thus completed wholly over automatic switches. Calls for re-numbered manual exchanges appear on intimators on "B" positions in the manual exchange required. Calls for "Outer London" exchanges are completed by an "A" operator at the outgoing junction board in the new automatic exchange.

At the time of the transfer, we may assume Holborn has about 8,000 lines, of which half fall in the "North" region and half in the "City" region. At the transfer we assume all these lines are brought on to the new Holborn automatic equipment and are reached over the same junction groups, whether their numbers are prefixed with "City 6" or "North 2," for the levels corresponding to these prefixes are multipled together. At the transfer, therefore, Holborn exchange contains only one 10,000 group, having third, fourth, and final selectors common to both "City 6" and "North 2" lines. When "North" exchange is made automatic, the lines which are to be transferred to the "North" region may be diverted to the new exchange, the junctions from the level in other exchanges corresponding to "North 2" would now be taken to third selectors in "North" exchange, those from the level corresponding to "City 6" remain connected to the third selectors in Holborn exchange.

Should the number of lines on Holborn increase beyond the capacity of the 10,000 group before "North" exchange is converted, a 10,000 group corresponding to "North 2" could be opened in Holborn exchange, and the junctions from level "North 2" in other exchanges separated from those from level "City 6" and connected to the third selectors of the new group. Lines with numbers commencing with "North 2" would then be cross-connected to final selectors in this new group, which would really form part of the switching equipment of the "North" region erected and working in an exchange in the "City" region.

A case in which an existing exchange area is to be divided between two regions has been described above. The arrangements in the simpler case in which it is comprised wholly within the one region will be easily followed. Our object in choosing the more complicated case is to investigate the problems which arise in it and to see whether the automatic system will prove flexible enough to enable us to deal with a case of this description without serious difficulty. Of course, it would be a simple matter to assign all subscribers in Holborn the prefix "City 6" and, on dividing the area when North exchange is converted, to change this prefix to "North 2." This is what would happen with the manual system on the occasion of a change of exchange areas. We have seen, however, that with the automatic system, if such matters are given consideration when applying the numbering scheme, the change is easily arranged for without further re-numbering. In fact, it can be made without either the subscribers affected or their correspondents being in any way aware of it.

This probably cannot be effected in cases where a new automatic exchange area is to be built up of portions of more than two or three existing exchange areas, because it is necessary to employ separate prefixes for the lines in each portion of each exchange area concerned, in order that the junctions over which they are reached may be separated at the time of the transfer. In such cases the distinction could be made for the two largest batches of lines, and the numbers of others changed a second time at the transfer.

Conversion of typical exchange in "Outer London" area.—Generally speaking, as mentioned on page 184, the conversion of the "Outer London" exchanges would follow after that of the "Inner London" exchanges is completed. There might be cases, however, where the installation of automatic equipment prior to this date is desirable. Let us suppose Redhill is such a case. As outlined on page 185, it would retain its present name and form a separate centre, obtaining its connections with other exchanges over a manual board just as Epsom does. Ultimately, we may assume Redhill is to form a sub-exchange on Purley and that it will be equipped with concentrating switches and fourth and final selectors only. It might well, therefore, be arranged in the first instance on the three-figure system with relay repeaters, using the ultimate fourth selectors as first selectors. When the time came for it to be included in the main system, the links from its relay repeaters would become junctions to first selectors at Purley, and its first selectors would become fourth selectors and be connected to the junctions from the third selector levels in Purley.

Final stages of the conversion.—As a further example let us assume that the "Inner area" is completely converted, that, say, Sutton and Richmond have

already been converted, and that Croydon is about to be converted. Since all the " Inner London " exchanges are converted, Croydon can obtain its connections with all " Inner London " subscribers by dialling, as shown in Fig. 9. Its own subscribers might be reached from all " Inner London " exchanges similarly (see Fig. 12). To enable this to be done, the Croydon subscribers must be given the full automatic numbers at the time of the transfer. Croydon subscribers can reach lines on the converted exchanges, Sutton and Richmond, with the dial, since these exchanges being similar to Croydon have also received the full numbers. There remain to be considered the calls to and from exchanges remaining manual and the isolated automatic equipments like Redhill, in " South " and the other " Outer London " regions. Since the lines on these exchanges retain their old exchange names, the Croydon subscriber cannot dial them and, following the standard instruction, calls in an " A " operator who completes these calls for him. At this late stage in the conversion the provision of a " B " switchboard with a subscriber's multiple in Croydon to handle the calls incoming from the remaining manual equipment would not be warranted. It would probably be more economical to provide junction positions equipped with dials to enable these calls to be completed over the switches. An alternative scheme would be to furnish the " A " operators on the remaining outlying exchanges with dials and junctions terminating in first selectors in the nearest automatic exchange in which first selectors are equipped. They could then set up all connections with converted exchanges without the help of " B " operators. If at this point the ultimate arrangements for completing trunk calls (see page 185) were adopted, the " B " switchboards in the automatic exchanges would no longer be required and could be finally recovered. Further, if at this stage each of the remaining manual exchanges were assigned a code consisting of the region name and two or more digits, the " A " operators could make use of the automatic system in completing " cross-London " connections, so that the need for manual junction centres would disappear. In completing a call, for example, from Waltham Cross to Reigate, assuming both these equipments were still manual, the operator in Waltham Cross might by dialling " South 86 " on a junction to Enfield, which we assume is automatic, operate a first selector in the latter exchange, a second selector in Battersea, and a third selector in Purley, and cause a calling signal to appear on a junction position in Reigate.

Concluding Remarks.

The authors think that the facts put forward in this review are sufficient to demonstrate that the changes that have already taken place and are now in progress among the telephone-using public and in the labour and manufacturing worlds, are such as to demand considerable advances in types of plant and methods, if improvements in the service and provision against increased expenses are to be made in the future.

It is apparent that little more than the present standard of service is to be expected from manual switchboards, and the expenses attending this type of equipment are likely continually to increase. Further, it is doubtful if this type can fulfil the ultimate demands of the service in large cities.

The introduction of mechanical operation offers striking improvements in service and a means of reducing those items of expense which show the strongest tendencies to increase, namely, administrative and operating charges and rent and other building costs.

There is now sufficient experience to show that we may, with confidence, avail ourselves of the effect of the much speedier service and greater economy of the " full automatic " system ; a half-way step in the shape of recourse to the semi-automatic system for the transition period is not warranted. For the ultimate conditions, this system is certainly undesirable, since it retains the monotony of operating and many other disadvantages of the manual system in an accentuated form.

While full automatic operation is to be preferred for the great bulk of the traffic, the authors are not suggesting in any way the total elimination of the operator. Trunk and private branch exchange switchboards will still require human intelligence in their operation. These classes of operating require the exercise of a higher form of intelligence, and are not monotonous. The inter-departmental calls on private switchboards, however, are decidedly of a nature calling for automatic methods of working.

With reference to tariffs, a proposal has been put forward for a " unit of telephone service " which should help to eliminate the undesirable features of the present rates and to reduce the amount of clerical labour involved. It places the charge for telephone service on a similar basis to that for electric light, and so would be readily grasped by the public. It is scientifically sound, and also offers opportunities for greatly increasing the revenue-earning efficiency of the plant during slack hours. Further, it enables us to make very readily those readjustments of the tariff which the mechanical system appears to demand, notably the introduction of the time element.

As to the time of the introduction of the automatic system, the immediate future is undoubtedly the most favourable, offering an opportunity which will not occur again. On account of the war, not only are the amount of plant and the number of subscribers affected less than they will ever be in the future, but the depreciation account is in a better position to stand the heavy replacement charges than it would be in normal times.

An attempt has been made to show by a study of the London area that there are no fundamental difficulties to be expected in the application of automatic systems to large cities, either in the ultimate arrangements or during the transition period. London is one of the most extensive and complex telephone systems in the world, and the authors think, therefore, that there should certainly be no difficulty in dealing with simpler cases.

The authors do not wish it to be thought that they have attempted to say in any way how the case of London ought to be treated. They have merely used it as an example in which they were likely to find in their

most pronounced form all the difficulties that might arise in dealing with large cities on the automatic system. The actual conversion of the London system is of course a matter entirely for the administration and its staff.

In conclusion, the authors trust that this paper will not altogether fail to draw attention to, and stimulate discussion of, the effects on the provision of telephone service of the recent serious changes in many factors.

The question is not merely a matter of the design and standardization of equipment. It is, as Mr. Kingsbury has pointed out,* "a complex engineering problem mixed up with a complex social problem," involving economical and social factors equally as important as, if not more so than, its technical aspect.

* *Journal I.E.E.*, 1911, vol. 47, p. 602.

The effect of these factors alone on the trend of events is certain to result in changes in methods and equipment, and he who ignores these factors must find himself in a short time swept off his feet by the full tide of public opinion.

The authors hope, therefore, that this paper may, to some slight extent, assist in securing the extension of British telephone systems on modern and efficient lines, in keeping with the changed conditions of the times, so that our large cities may at least be abreast, if not in advance, of those in other countries. For the facts here brought forward are becoming universally appreciated, and there is no doubt in the authors' minds that all the large cities of the world, including even New York, will in the course of a few years be equipped with the automatic system.

Discussion before The Institution, 15 May, 1919.

Sir William Slingo: It is very remarkable that only in 1912 the first experimental automatic exchange was opened in this country, and if we deduct the period of the war, during which there was really no progress made but rather a retardation, the fact that we have some 14 of these exchanges now working shows that we have tackled the problem with a certain amount of earnestness. The problem is very difficult, and I fancy that the authors have purposely placed on one side, I will not say ignored, one of the first difficulties that we must encounter, namely, that in any application of the automatic system we must employ the same system throughout an area. Now London is a big area; there are at the present time 71 exchanges and there are three firms who are capable of manufacturing automatic apparatus on a large scale. Under the present system whichever one of those firms obtained the contract for the first exchange would have almost a prescriptive right to all the rest. I think it will be conceded that it is of the first essence that we must either standardize or unify our system, or, alternatively, as consumers we must come to some arrangement with the manufacturers, so that when we have opened our first exchange and paid the price, we do not pay on an upward sliding scale for the successive ones. There are ways out of this difficulty, by combination, and by fair dealing, in which we could employ, if need be, all three contractors upon different parts of the equipment. That is one of the problems which remains to be solved. So far as the principle, or rather the application of automatic working is concerned, I may say that the one great thing which I wanted to do, in order to bring a really large town into our purview, was to get a five-figure exchange opened and working. Such a five-figure exchange was opened just 12 months ago in Leeds, and since then it has given very great satisfaction. If a five-figure exchange can give satisfaction, why not a six? And when we get to six, we can work London. That was the line of reasoning which, notwithstanding the war, induced us to press forward the work at Leeds and bring it to fruition. So far as the financial aspect of the case is concerned, there is one little point upon which I think I must cross swords with the authors, namely, that the life of the manual plant must be shortened in order to get an increased depreciation account to pay into the automatic. It seems to me that is the wrong line of reasoning. However much one may want to favour the automatic, it is not quite the thing to turn down the item which it is superseding, or to kill it before it is dead. What I mean is this, that if we wilfully murder the manual, shorten its life, then the loss that we get on that account must be debited against the automatic. If we do not do so, someone else certainly will. The automatic, if it is going to justify itself—and I am certain that it will—must take account of all costs that are incidental to its adoption. That an automatic will work, can work, and does work, is beyond doubt. The one great problem is to satisfy the holders of the purse-strings that it is a profitable undertaking. Although the capital cost is probably some 40 to 60 per cent higher in the case of the automatic than with the manual, I am satisfied that the annual cost of an automatic is less than the annual cost of the manual, mainly on account of the labour bill and the smaller premises required. But since operators' wages have risen so high, never to come back to their old level, there can be no question that the automatic system will justify its installation. I am very glad we are in front of New York in that respect. They have not yet got as far as we have, but they have reached this stage: they are satisfied that under present conditions the automatic is the proper financial proposition.

Mr. J. E. Kingsbury: Sir William Slingo expressed some anxiety as to certain possible difficulties if the automatic system were to be adopted for the purpose the authors suggest, but I doubt if Sir William's anxiety on that score is justified. We may be sure that the Post Office will be well able to take care of themselves if the automatic system becomes a practical proposition. There is one point in the paper to which I particularly wish to refer. The authors say that this is a suggestion put forward for discussion: they disclaim any intention of regarding it as a finished scheme for London. I want to associate myself with the authors in those remarks. I look upon the change as one

which, if and when it is made, must be made with the very greatest consideration because the Administration has an immense responsibility in re-arranging the telephone system of any large area, and particularly of London. Now, on the subject matter of the paper there are two points to consider—the telephone area and the method of working it. The first thing I should question would be the area. Why, in any re-organization, should we maintain an area which never was intended as a telephone area at all, but which has grown from various causes into what is now regarded as the London telephone area? Is there sufficient justification for providing direct communication with places so distant from the centre as Reigate and Waltham Cross? I do not know how far any modification or reduction of that area might facilitate the carrying out of a scheme such as the authors suggest, but I believe it would be advisable to take advantage of any new arrangement so as to revise the area. With regard to the method by which it should be done, or in other words the machinery by which it should be done, Sir William expressed his surprise at the promptitude with which his ideas had been realized, at least to the extent of the presentation of this paper. I think we must remind Sir William that he held those ideas in the dim and distant past before the war. No matter what anybody's opinions were on methods of telephone switching, there is nobody who can alter the facts of history, that all questions of labour and pay and conditions are totally different to-day from what they were five years ago. But the problem is now as then mainly a question of finance; and if I wished to criticize the paper I should say that the authors have omitted a very important feature in leaving out finance. I agree they cannot very well help it. To prepare the necessary estimates is beyond the authors' power or anybody else's at present, but it will have to be done before the decision is made. There need be no real doubt as to the working of an automatic system. So far as irregularity in service is concerned we may remember that for certain specific work machines are more exact than humanity. Babbage tells us that he set about the invention of his calculating engine because of the uncertainties and unreliability of human calculators. There is very much in common between Babbage's calculating engine and an automatic telephone system, the difference being that an automatic telephone system is not only a calculating machine but is also a transmitting device over a very long distance. Having given credit to the well-constructed machine for reliability in the work it is designed to do, we must also remember that it cannot go beyond its design. It is effective within limits and it is useless to expect it to go beyond those limits This is a further reason for the utmost care in the preparation of designs and to forecast the possible developments of the service. There is just one point upon which I must find fault with the authors. They suggest that the prevalent objection to exceeding four figures has its origin in the fact that a manual exchange is limited to 10,000 subscribers. We know perfectly well that one of the methods of testing the intelligence of backward races is to see how far they can count, and if we want to test the intelligence of our less backward friends we may see how many figures they can remember after a brief glance. Why do the County Council limit the numbers of motor cars to four figures? I think it must be because they want the number to be accurately remembered after quick observation. Make them five and see how many observations would be correct. In the case of manual operating there is no question about it; the four-figure theory is not imagination but is a matter of solid fact. Every figure added increases the risk of unreliability in repetition and remembrance, but when one comes to automatic working I do not think it has the same importance. Automatic working will inevitably require a more measured operation, and we shall undoubtedly take care that we have our numbers before us. So that on the question of numbers we may the more readily give way to the necessities of the situation whether it be 4, 5, or 6. That brings me to this point: that however few or many there are I do not like any of them to be wasted. The authors give us a picture of the south area. It will be realized that in the word "south" we have the equivalent of an additional figure. The ultimate lines for Merstham are assumed to be 422, and 1,000 lines are allowed. What will happen if the number of subscribers grows beyond the allowance? Why should we not have an exchange selected by a figure or figures and then start afresh for the individual lines in that exchange? It would have the advantage for the transition period that the subscriber would select the exchange he wants. If it were a manual exchange it might be possible to arrange that his automatic operation put him into connection with a disengaged operator at that local exchange. As I am not an automatic expert I have not gone into details, but I should like the authors to indicate whether there are any insuperable difficulties in obtaining some method which would avoid the allocation of any given numbers for a particular area which may or may not—probably will not (in some cases certainly will not)—provide for the ultimate requirements, whilst in other cases the numbers may be wasted. Groups of, say, 10,000 with an additional number for each group would allow for the natural growth of each district without limit.

Colonel C. B. Clay: There is no mention in the paper of any particular firm or company, and I think that is just as it should be, but it is a little unkind of Sir William Slingo to say there are only three firms who could deal with the manufacture of plant. I do not know how many men Sir William Slingo wants in a factory. I can control a factory now that will put in 3,000, and I do not mind doubling it if it is necessary.

Colonel Sir A. M. Ogilvie: We are all agreed at the present time as to the good results which have followed from automatic exchange work in this country and in America so far as it has been developed. As regards cost, Sir William Slingo has told us that it has "proved itself in." I think also it may claim the advantage of a considerably increased efficiency. It has wiped out the operator's errors; it has probably not increased the number of line and apparatus faults; it has made the calling subscribers' errors, perhaps, a little more than they were, but at the same time, seeing that

they are his own errors and are recognized as such, they do not affect his opinion of the service in the way that his errors do at present. At the same time the distant subscriber is made answerable by the system to the calling subscriber for the faults which he commits; so, on the whole, the system undoubtedly commends itself to the public in a very marked way. These advantages we might expect to be continued to some extent even in a system as large as that required for London, but there is no doubt that even if we could at once have a unit-rm automatic system in the whole of London, there would be difficulties which have not existed in the case of those automatic systems at present working. They are mainly and essentially single exchange systems. The paper has shown us the complexity of the automatic junction system required in London, and there can be very little doubt, I think, that under the automatic system for a multi-exchange system such as London we must have a largely increased expenditure on line plant for junction lines as compared with the manual system. The instance the authors give in which an Esher subscriber will call another Esher subscriber by using junction lines through Kingston and Wimbledon is rather striking. There can also be little doubt that if we are confined to groups of 10 junctions we shall have waste margins on the very numerous groups, and in the aggregate that will tend to increase the number of junction lines required. Then again there is the difficulty of the six-figure numbers, which I think probably could be got over. The experience of five-figure numbers up to now has shown that those difficulties are much less than were anticipated. The greater complexity of the plant, I suppose, will lead to some increase in maintenance cost, and also to a greater liability to faults. Those objections probably are not insuperable, and if the problem of London were to put in a new and complete automatic system without any relation to anything that existed before, we should certainly feel much more happy in going ahead. As it is, I think the paper shows the extraordinary difficulties that would arise in the gradual conversion of such a huge manual system as London into an automatic system. I do not know how many years it would take, but one might give a guess—10 to 12 years at a very moderate estimate—and during that period the public and the service would have to face a considerably increased amount of difficulty in working and a considerably increased cost. For the reasons which the authors have given, it may be necessary very soon to face those difficulties, but there can be no doubt that during the period of transition the difficulty and the expense of working the system will be great. I need perhaps only refer to the difficulty which the authors describe in working between the automatic and the manual subscribers. From the automatic subscriber to the manual subscriber we must have an automatic system or a dialling system or some equivalent system, the cost of which will have to be added to the cost of the manual exchange and to the cost of the automatic exchange, and be a net addition to the whole cost of the system. Then again, for incoming calls from manual to automatic there seems no way out of it but that during the transition stage we must keep a multiple on the "B" side at the automatic exchange. That, the authors suggested, might be arranged by the conversion in an existing exchange of the existing "B" multiple; but it hardly seems to be practical, because that "B" multiple must be kept in use until the whole of the exchange can be cut over, and therefore we must put in a new "B" multiple in the first automatic exchange we make. We may then move out our "B" multiple to our next exchange, and so on; but the whole process will involve additional plant; it will involve a certain amount of removal and alteration, and it will require plant which, after all, is subject to a good many faults and interruptions. So far as I can see, for many years, until the great majority of the manual exchanges have been converted, we shall have the aggregate of faults arising due to both the automatic and the manual systems; we shall get very little improvement in the efficiency of the service from the small part of it which will be done exclusively by the automatic plant, and we shall have as much, if not rather more difficulty in working the manual part of the service.

Mr. Charles A. Baker: A previous speaker (Colonel Ogilvie) gave the meeting to understand that tariffs may go up rather than down; it is very difficult owing to the war to appreciate what a tariff should be now as compared with what it used to be before the Post Office took over the telephones, but lower rates were customary up to 1912; the rates then went up, and they have gone up again since. In London one cannot get a telephone at all now under £6 10s. per annum: outside the Administrative County one can get a telephone for £5 10s. per annum, assuming there is room for additional circuits on the posts, but those are quite high prices. It seems to me that, for local work only, on any exchange there ought to be a much lower tariff based on the same scale as that enjoyed by the provincial towns. Croydon has been mentioned; it comes in the metropolitan area, and is deprived of the advantage of a cheap local service. I understand the justification for the high tariff is that once connected with the system in Croydon (or any other part of London) one has an enormous number of subscribers to whom one can talk. That is all very well, but on the other hand the Telephone Authority has an enormously large number of subscribers in a comparatively small area, or say per square mile. Officially I have some 770 instruments connected to the Post Office system, and they are all attached to the central offices in London within a stone's throw one office of another; many of the instruments are "extensions," part of the cost is for junction lines, exchange lines and so on, but it is all a very condensed area, and the average cost of those instruments is £7 10s. each per annum. If the Telephone Authority had to run miles of wire to each of those instruments I am inclined to think that £7 10s might not be an excessive price, but for nearly 800 telephones in a condensed area £7 10s does seem to me to be a high price, and in my opinion, many thousands of people are prohibited from using the telephone in the London area in consequence of the high price. I am not quite sure whether the telephone users have to pay for the telephones put at the disposal of the Government Departments:

one knows, of course, that the Government have free use of telephones and free use of the Post Office generally: if no transfer of accounts is made, then of course the telephone user is taxed to pay for the Government use of telephones. It almost seems that London is too big for the telephone system with which it is now equipped; so many exchanges make it almost an impossible problem: the provincial towns are more within the limits of an efficient system of telephony. Another point that I should like to emphasize is security against breakdown. During the storm which occurred a few weeks ago it was reported in the Press, I presume correctly, that some 11,000 subscribers' lines were put out of action. It was not an exceptional storm, and it seems to me that the Post Office ought to use some higher factor of safety in the construction of their overhead lines and equipment generally, so that we should not suffer from a breakdown such as this. Not many months ago I was in the North of England where they were suffering from a similar breakdown; the storm on that occasion did not affect London, but with the high subscription which is demanded, I think we are entitled to very much greater security. One other point I want to deal with is the question of meters—always a very interesting one to the subscriber. Of all meters with which I am acquainted the telephone meter used to record the number of calls initiated is the worst. It is put on the back of the exchange somewhere or other and the subscriber never sees it, although a privileged person may perhaps be allowed to have a look at it. A long time ago—in connection with electric lighting—I had to deal with an early design of electrolytic meter: the accounts were rendered on the basis of the weight of zinc deposited on the plates: these electrolytic meters were quite useful, but the consumers did not like them because they gave no indication on any kind of dial of the daily or monthly consumption: the plates had to be removed and the consumption calculated after carefully weighing the plates to ascertain the increase as compared with the weight of plate originally put in. The same objection, in a more aggravated form, must be raised against the telephone meter, viz. that it gives the subscriber no information as to the number of calls which are being registered against him from time to time: in case of dispute the Postmaster-General assures him that the record is there, and he has got to pay for it. If some reliable description of meter could be put on the subscribers' premises, near his telephone, so that he could check the readings, that would in my opinion be a very great advantage, and would at least establish an equitable basis on which accounts are made out against the numerous subscribers who adopt the "message rate" system.

Mr. J. Hedley: It may be safely stated that the experience so far obtained with full automatic exchange working justifies the authors' opinion that an improved service is afforded to subscribers. With regard to the "wrong number" trouble which is common to both manual and automatic, the statistics of the Post Office confirm the figures in the schedule supplied on page 165. The proportions are, approximately, a total of 1·6 per cent for automatic and 3 per cent for manual. The records indicate that, of this total, 1·1 per cent under automatic is due to subscriber's error and 0·5 per cent due to the switching plant; whereas under manual 0·8 per cent is due to the subscriber and 2·2 per cent to the manual exchange operator, thus confirming, as might be expected, that the machine acts more reliably than the operator. It is only fair to state that these figures are obtained by service observation operators who cannot always find out the number of the called subscriber when he replies, and consequently having only a record of the number demanded by the calling subscriber she must use her discretion, and generally the error is scheduled against the exchange operator, e.g. the 4·7 per cent shown on page 165 most probably includes many subscriber's errors. The measure of the grade of service should therefore be taken from the total percentage of wrong numbers. I am sorry that the authors have not made any reference under technical problems to the scheme of working private-branch-exchange subscribers in automatic exchanges, when the number of exchange lines exceeds the capacity of the bank contacts. For 10-contact systems there would be many cases where the needs of the London private-branch-exchange subscribers cannot be fulfilled, and I should like the authors to say what scheme is recommended for such service. There are means of overcoming the difficulty and I think the proposals should be referred to in a paper of this character. There is also another technical problem to which I should like to refer. The calls originated by automatic subscribers for other exchanges are recommended to appear before the manual operator on an intimator. What scheme would the authors adopt for metering these calls? I am of opinion that such facilities can be afforded, but it is desirable that the scheme should be fully worked out by contractors. With regard to the lantern slide shown of the intimator, I think the idea is a very good one, but it is questionable if sufficient room for the lamp jacks will be available in the "B" position multiple field, and it is therefore probable that the keyboard method, where space is generally available, may have to be resorted to. In connection with the handling of incoming junction traffic I cannot agree with the authors when they recommend scheme 3 on page 184. Three schemes are suggested: (1) where the distant manual operator dials the number direct; (2) where the call is received in the automatic exchange by an operator and is completed by means of a keyboard sender; (3) recommends the utilization of plug-ended "B" positions transferred from other exchanges and completing the call in the multiple of the subscriber's line. In my opinion scheme 3 is fraught with difficulties. It demands that during the short period between (*a*) the "B" operator testing the multiple jack of an automatic subscriber's line with the tip of the plug and (*b*) the plug pushed home to make connection, it shall not be possible for any automatic switch to test and pick up the automatic line concerned. Such co-operation between automatic machines and operators does not appear to be practicable and double connections would undoubtedly occur; probably only to a small extent, but as the danger is existent the scheme should not be countenanced. In my opinion it is essential

that all incoming calls should be completed automatically so that the connection with the wanted subscriber's line is always dealt with by the switching plant, thus eliminating any chance of the double connection referred to. With reference to the wholesale changing of subscribers' numbers in Inner London I must confess I do not quite like the idea. All the facilities referred to in the paper can be afforded if we transfer the exchanges one by one. It is next to impossible for subscribers' numbers to be definitely assigned in advance in large areas like Inner London, in the most economical way from a cabling standpoint, which will cater for the whole of the transition period of, say, 10 years; consequently some of the subscribers' numbers would need to be changed a second time and this must be avoided. I think therefore it would be very much better to draw up a really sound scheme for the transition period and deal with each exchange one at a time.

Mr. A. H. Preece: I should like to make one or two short points. The first is this. Why, in automatic exchanges, in the dials is one limited to the digits of 10? Why should not we have letters? Would not that to a certain extent increase the scope of the automatic exchange? I wish next to refer to capital cost. I happened recently to be dealing with a case abroad, where it was a question of putting down a new exchange in a town, now of 20,000 subscribers, with future extensions probably to 100,000 subscribers. Everything led one to think that it was an ideal place for automatics; two languages are spoken, the operators are not very efficient and there are no trunks. We were instructed by the board of the company to obtain tenders for both automatic and manual systems. The tender for the complete automatic switchboard was practically £50,000. The lowest tender for the manual was £24,000. We had the actual costs of the existing operating charges, and by means of those tenders we were able to calculate fairly accurately, allowing 8 per cent interest and 10 per cent depreciation, that the additional annual cost of the automatic exchange would be £6,000 a year. Under those circumstances we were obliged to recommend the adoption of the manual system for the new exchange. The automatic system would have reduced the number of operators from 60 to 12. Each operator now costs, on the average, about £3 per month; and it is only a matter of calculation to show that if the cost of the operators came to as much as £8 per operator per month, the balance would have been in favour of the automatics. I understand that in New York the Bell Telephone Company are seriously considering, if not actively undertaking, the design of the automatic system for the whole of New York, based on the fact that the cost of operation per operator has now exceeded £8 per month. I think that in London we are getting very near that stage, and no doubt in a short time the justification for automatics will be very clearly shown from a financial point of view. I would here remark that the capital cost at the present time is of course exceptional, and the figure of £50,000 may come down in the future to £40,000, or even less, but we are bound to face facts as they are at present. It seems to me that in an area such as London we have to educate the public, and I would submit that a scheme such as the authors have put forward should, if possible, be carried out in some way whereby the public are gradually educated to it. Anything involving six figures is, I think, going a little bit too fast for the public, and I have grave doubts whether one can educate the public up to using accurately a six-figure dial.

Mr. A. J. Stubbs: I think that the attitude of the engineer in this connection should be frankly progressive, but that the attitude of the administrator should tend to be conservative; the point being that although we are certain of the success of the automatic system, we should not give the public any reason to infer that the present system is not a good working system. When we speak of the economic value of the plant, for instance, to throw out the existing manual plant obviously would not be sound economics; nor, even if it were possible, would be very rapid adoption of the automatic, because, as the authors admit, the present stage of design and development is not such that we can claim the plant to be standard. If we are to have a system that will be thoroughly efficient we must work steadily forward until the automatic plant has been standardized more or less with the thoroughness that characterizes the design of the manual plant. I suggest, therefore, that as telephone engineers we should make a special point of not admitting that the present system is essentially not the best that proper and reasonable procedure admits. We have got at the present day every stage from the latest switchboard back to the magneto board; and reasonably so; and in 10 years' time we shall be in the same position—we shall have the latest board, back to some manual system now in existence; and the public as well as we will have to recognize the fact that the highest practicable efficiency of a system is consonant with the continued service of plant that is not of the latest type.

Mr. F. M. Ward: I do not entirely agree with the authors that a higher voltage than has been standard for central battery working in the past would be advantageous in every way. I agree that perhaps a 50 per cent increase would be justified on account of the improved transmission, but I think a higher-resistance transmitter would also help in this direction. High voltages are undoubtedly more exacting to the line and cable work, and in this connection it may be of interest to telephone engineers to mention that I had a unique opportunity of comparing the effects on the insulation of what are practically the high and low voltage limits of automatic working and in which all the conditions were equal except the voltage. The installation was an automatic one of an early type, in which a split battery was used in such a way that the "A" line was connected through a feeding coil to 60 volts and the "B" line through a similar coil to 30 volts—that is to say, the "A" line was always 60 volts and the "B" line 30 volts above earth. The lines were entirely in cable, and tests invariably showed that the insulation resistance of the low-voltage line of a pair was very much higher than that of the higher voltage line. Neither do I agree that higher voltages reduce the maintenance expenses on relays, as the authors suggest. I have had experience with automatic

working on voltages ranging from 24 to 60 volts, and have found it more difficult to eliminate disruptive sparking on the higher voltages. It is obvious, I think, that the higher the voltage employed the more risk there is of an arc once started being sustained. I think it would be as well to keep these points in mind before standardizing the voltage for automatic systems. The authors on page 169 touch on the subject of ventilation without risk of dust and damp. I think too much has been made of this in the last few years, and I cannot see why the contacts on automatic switches and relays should require more careful protection than similar apparatus in manual exchanges, provided, of course, that a proper contact pressure is employed. Referring to the statement on page 179 regarding calls to be reverted to the sub-exchange, and that junctions outgoing to the first selectors may be freed and the switches released after it has been determined that the call is for the local exchange, I may say that circuits have been developed which render the engagement of such junctions entirely unnecessary unless the call is actually going out of the local exchange.

Mr. B. O. Anson: It is clear to those who have been in touch with the subject of automatic telephony during the last few years that there is now quite a different attitude of mind with respect thereto from what there was some years ago. When Mr. Laidlaw read his first paper the question was "Will the Automatic System work?" To-day it is not a question of whether it will work, but whether the manual system 10 years hence will be able to cope with the traffic. The authors support their position with regard to the efficiency of automatic as compared with manual plant by statistics. I should like to supplement their figures. A four-figure automatic exchange has been watched by the Post Office for a considerable time as compared with a manual exchange, and we get average figures like these: The time taken by the subscriber to dial is 4·7 seconds, which carries the call up to the point where the wanted subscriber's bell rings; a similar stage at a manual exchange is reached in the best circumstances in 11 seconds, but at the present time a much longer period is occupied. The time taken in an automatic exchange to disconnect a terminated call is $\frac{1}{3}$ second, but at a manual exchange originated calls are not disconnected until 6 seconds have elapsed, and the delay in disconnecting inward calls is still greater. At an automatic exchange the engaged signal is given to a calling subscriber in 6 seconds, as against 13 seconds in the manual case. The called subscriber and his line are held by an automatic exchange for a total of 17·5 seconds (operating time), as against 31·7 seconds during which the operator occupies the attention of a subscriber at a manual exchange in connecting and releasing a call. Each of these cases includes about 12 seconds that are occupied in waiting for the called subscriber to answer his bell. In the automatic system irregularities occur in 5·9 per cent of the calls, as against 30 per cent on the manual system. In this latter connection it is interesting to note that the irregularities due to subscribers are lower for the automatic than the manual system, showing that a subscriber "dials" more accurately than he speaks. On page 168 the authors deal with the question of costs and state that the amount of raw material in a large automatic exchange is not very different from that in a corresponding manual equipment. That being so, and having regard to the fact that in automatic equipment there is a much greater proportion of press tool and repetition work, and less direct labour than in manual equipment, one would expect that eventually the first cost of automatic would be lower than that of the manual plant. The question of depreciation is important, and I think that the corelative subject of the comparative life of plant should rest upon fact rather than expediency. The authors say that automatic will have a longer life than manual plant. I agree entirely. At a manual exchange practically the whole of the *troublesome* engineering is centred in the mass of cables and jacks known as the subscriber's multiple. Even after long years of experience it is not the practice to renew the subscriber's multiple, and when the jacks lose gauge with the plugs or the cable deteriorates the exchange has come to the end of its useful life. There is no such controlling factor in the age limit of automatic equipment. Every part of this equipment is capable of renewal. The plant is erected in units, and if any unit needs to be thrown out of service for purposes of renewal it is relatively a simple matter to install a temporary unit to replace it while the work is in progress. The difference between automatic and manual plant in this respect is evidenced by a case which occurred some time ago in which a leakage of sulphuric acid from the floor above destroyed the wiring of one of the automatic units. Any experienced telephone engineer will realize what a serious thing it would be for a similar accident to have occurred to a subscriber's multiple. The authors referred to a meter which can be used for registering calls having different cost values. Unfortunately they did not give any details in the paper and therefore it is not easy to criticize their proposal. It is evident, however, that they attach considerable importance to this device, but a word of warning is necessary. If the instrument is mechanical in type and is designed to perform four different operations where one is now performed, it is an added intricacy on the system and to my mind is wrong in principle. Meters should be simple mechanically. If, however, it is as simple in design as the existing type, and is adjustable so as to follow the changes of tariff which will arise from time to time, then undoubtedly their proposal is an important one, as it would render automatic working practicable as between adjacent cities that have a small trunk fee in respect of calls from one to the other. The transition processes in a large area such as London are of great complexity. The requirements of machinery differ very greatly from those of human operating, and it is necessary to meet both sets of requirements for a number of years. The authors suggest the changing of all the subscribers' numbers, and some wholesale change of this kind appears to be necessary. The most promising scheme that has yet been proposed appears to be one which involves changing the whole of the exchange names in preference to the whole of the subscribers' numbers. An example will perhaps make this clear. An existing subscriber,

East 4136, is part of a system which is to be worked automatically upon a six-digit basis. The new number suitable for automatic working might be something like 254136, in which two digits have been placed in front of 4136. Now this number would be very objectionable when used on calls passing through manual exchanges not yet converted to automatic working. By selecting 10 letters, preferably common consonants, the digits 25 might be replaced by DS, and we should then have DS4136. If now some word be chosen instead of East having D and S as the initial and final letters, such as "Docks" we get Docks 4136. If now a dot be placed under the D and S, thus Docks 4136, we have a device which meets all requirements. The dials would show letters as well as digits and all operators and subscribers on manual exchanges would use the expression Docks 4136, whereas automatic subscribers would dial DS 4136, the two dots placed under the letters being an indication on reference to the Directory that these symbols are to be operated on the dial. The change in directory could be made long in advance of the introduction of automatic working at a given exchange.

Mr W. Aitken: The telephoning of London is a very big question requiring very careful consideration. I believe with the authors that the full-automatic system only can give London an efficient telephone service. One of the most important features affecting the efficiency of the plant and the popularity of the service is the method of charging for the service given. The authors advocate a system based on a "unit of telephone service." "The rate of consumption of a unit according to amount of plant involved" is theoretically good, but in practice will introduce great complications. Judging from known corresponding methods of charging according to the amount of apparatus brought into use on a call, additional apparatus, to influence the subscriber's meter, must be associated with each junction, and this apparatus is varied according to the length or importance of the junction. Such devices complicate the plant and increase the capital cost and maintenance. In an installation such as that described, the cost of subscribers' meters and junction equipment will probably exceed £1,000,000. It is impossible to place a figure on the maintenance charge, but it must be considerable, and it must be borne in mind that all complications increase the possibility of troubles from faulty lines and apparatus which ultimately affect the service. The simpler the system is kept the more efficient it will be. After considering such suggestions for charging schemes one is forced to ask: what alternatives are there? And it may prove worth while considering a return to the "flat-rate" system or a modification of it. This, at first sight, may appear a retrograde step, but the automatic system puts many aspects of the telephone question in a new light. In the United States a large number of the exchanges work on the flat-rate system. It is, or used to be, argued that the apparatus being provided it costs little more to allow the subscribers to put through additional calls. It is found in practice that the calls are shorter (83 seconds instead of 2 to 2½ minutes) and consequently that fewer junctions are required per 1,000 calls in the busy hour (30 junctions in a common group against 46 to 55). There will be a greater proportion of frivolous calls, but these would not likely exceed this difference. The telephone will not be used so freely on a message-rate system as on a flat-rate one. Subconsciously the cost will be counted each time a call is made and full value will be required in duration if possible. It is therefore impossible to advocate or encourage the telephone habit, particularly as regards the social side of the problem. The flat rate system is also preferable for the small user with party lines. Otherwise a fairly expensive coin box has to be fitted alongside the telephone, into which a fee has to be deposited for each call. These boxes discourage calls and multiply troubles. It is usually argued that the small user partly pays for the calls of the big user on the flat-rate system. There is a little truth in this, but I do not think it more serious than our method of charging for water. Two similar adjacent houses pay the same water rate but the occupants of one may use 10 times as much water as the other. They both have the right to use the same amount. The telephone should be as freely used for a fixed charge, and for small users this might be paid quarterly. In an automatic system, owing to the operating of party lines mechanically, these can be freely installed and, therefore, the small user may have a half, or a quarter share of a line, fitted with selective ringing, and possibly with secret or non-interfering talking. For still smaller users, in flats and workman's houses, the eight-party line may be used. The bigger user would have a single direct line for his sole use, and the number of lines would be increased as required according to the extent of the business (the number of calls per direct line should be restricted so as not to interfere with the efficiency of the service). There should be different rates for all types of lines, for business premises, and residences. It might even be possible to assess a telephone rate in the same way as the water rate. The saving in staff for reading meters, rendering accounts, etc., would be very great, and the irritation of disputed accounts would be eliminated. It seems to me the subject is worthy of very careful consideration from both an economical and efficiency point of view. If full automatic private branch exchanges are to be allowed, it follows that in many cases six figure calling will become 7, 8 or 9 figure calling, according to the size of the exchange. When it is remembered that delays in calling all the digits of a number, due to again consulting the directory at any state of the call, maintain a corresponding number of junctions and switches in ineffective use, it will be appreciated how necessary it is to aid the subscriber in every possible way to call correctly and without hesitation. I do not like adding names of areas to a figure in the finger hole. In badly lighted places, or due to shadows in well lighted places, the names cannot be read. In the United States the figures have been prefixed by the first 10 letters of the alphabet, and the relative positions of these letters readily become known so that even the blind can manipulate the dial. It has also been the custom to divide the number into syllables, as 27 39 40, to assist the memory. It may even prove convenient to give the subscriber a small hand device with a series of discs,

of the telephone-meter type, which can be set from the directory and held in the left hand whilst dialling with the right.

Mr. F. G. C. Baldwin (*communicated*): The subject of automatic telephony is one of considerable importance to this country at the present time and the paper is an exposition of one of the most difficult features of automatic telephony, viz. its application to the requirements of a large and congested telephone area. In this connection perhaps the title of the paper is a little misleading as it treats of a good deal more than is conveyed by the term "Telephone Service of Large Cities." It is but a few years ago that telephone engineers responsible for the telephone service of this country expressed doubts upon the following points:—(*a*) Whether automatic telephony could be successfully applied in this country owing to the adverse climatic conditions. (*b*) Whether the British public would welcome or even accept a change from manual to automatic working. (*c*) Whether the advantages to be gained by the introduction of automatic working outweighed the advantages which would be lost. (*d*) Whether the automatic system would reliably fulfil its functions. (*e*) Whether the costs of automatic working were such as to justify its introduction in place of the existing systems. During the past six years several automatic exchanges have been brought into use in different parts of the country and the results obtained have undoubtedly dispelled the doubts which existed in so far as the points enumerated above under (*a*), (*b*), (*c*), and (*d*) are concerned. As regards the cost of automatic as compared with manual working, I am not aware that any reliable figures have been published. Up to the present time the introduction of automatic working in this country has been confined to the conversion of isolated exchanges and has not been in the direction of the establishment of automatic working on a large scale over a complete system of exchanges. In my opinion the economies to be derived from automatic working will only be secured when such systems as a whole, and not isolated units, are converted. During the past five years I have had an opportunity of closely observing the working of an automatic exchange since it was brought into use in 1914, and of studying the attitude of the telephone-using public in regard to the automatic service, and I think I am quite correct in stating that not one of the subscribers would, of his own choice, elect to revert to the old manual system. It should be borne in mind, however, that the automatic exchanges opened in this country have so far replaced magneto exchanges, and the advantages secured to the subscribers have therefore been greater than would have been the case had the replaced exchanges been of the common battery type. The authors have demonstrated the advantages which the automatic system secures in the increased rapidity of connection and disconnection. Taking only one call into consideration, where the difference is measured in seconds, the improvement is striking enough, but when it is remembered that this improvement applies to the whole of the calls transmitted over the system, the economy is very far reaching. As a matter of curiosity I have estimated that for an average exchange with 1,000 working subscribers' lines the annual saving in time which would accrue to the whole of the subscribers by the substitution of an automatic for a common battery system would exceed 10,000 hours, or 10 hours per subscriber per annum. In a large city like London where the percentage of junction traffic and consequently the number of junctions to carry that traffic is exceedingly high, this feature of the automatic system is of particular importance and should secure considerable economy in junctions.

Mr. W. W. Cook (*communicated*): The authors have excluded from the scope of the paper any attempt to demonstrate that it is financially desirable to install an automatic system in London. Two reasons are given for this, the first—a quite legitimate one—that such a study can only be undertaken by the Post Office, and the second, that prices now are so abnormal that it would be difficult to get agreement. This may be so, but the difficulties of the situation do not justify anyone—even a Government Department—embarking on an undertaking of this magnitude without the decision being endorsed by a carefully prepared estimate of the results, based on a thorough study. It is undoubtedly true that the course of events during the last few years has been in favour of automatic, the principal factor being the increase in operating expenses. It must not be thought, however, that all the factors are working in the same direction. As everyone who has carried out investigations into the relative expenses of the alternative systems knows, the outstanding trouble in justifying automatic apparatus is its high first cost. Although the authors look forward to reduced costs in the future, it must be remembered that a future reduction in first cost is no inducement to spend money now, in fact, it is a deterrent, and if manufacturers wish to hasten the development of automatic apparatus it is necessary for them to devote their attention to reducing its price. I think the authors do less than justice to the manual system; for instance, I do not agree with their conclusions regarding the alleged monotony of operators' work. I am very glad to see that they take quite a sound view of private-branch-exchange working in view of the prevailing tendency to look on everything from the mechanism point of view, instead of devoting sufficient attention to ascertaining what are the traffic requirements and then to the mechanism necessary to attain the object. I look on the development of private-branch-exchange working on sound lines as one of the best arguments that can be put forward in favour of full automatic working, because if we look forward to a great increase of these lines, and if proper provision is made for training private-branch-exchange operators, we are getting a great many of the advantages of semi-automatic working, as a large proportion of the calls will be handled by an expert operator who can, provided the importance of the point is realized and the matter properly organized, be of great value to the administration. Another feature, which is not mentioned in the paper but should not be neglected, is the service observation. This has done much in the past to reveal weak parts of manual service and is really more important still in automatic working, but I do not think that sufficient attention is being directed to this question.

With reference to the idea of varying the charge for a call according to its duration, and possibly according to its incidence, I am rather inclined to think the disadvantages of the method would more than outweigh its advantages.

Mr. T. B. Johnson (*communicated*): There seems good reason to think that the question is not whether the automatic system is suitable for London, but whether any manual system can satisfactorily meet the requirements. It will be seen from the large scale diagram on page 175 that within the areas marked Victoria, Piccadilly, City, and Bank, there will be 440,000 subscribers' lines—necessitating even with the most careful distribution at least 44 (and probably 50) manual exchanges. No fewer than 40,000 of these subscribers' lines are concentrated in seven of the sections included in those areas, thus necessitating at least 40 to 45 manual exchanges where four or five automatic exchanges will meet the need. When we consider the difficulties of obtaining suitable accommodation for 44 to 50 large exchanges, and the enormous number of junctions that would be saved (bearing in mind the fact that the traffic between adjacent exchanges is usually of the heaviest character), one can realize something of the saving which will be effected by the establishment of automatic exchanges. The opening of each manual exchange would necessitate a re-arrangement of some of the subscribers' lines and numbers, which would be obviated once the exchanges became automatic. The difficulty and risk which appear to be thought to be involved in the use of five- and six-figure numbers are largely exaggerated, and the authors are probably correct in thinking that the idea that four figures only should be used is largely owing to the fact that manual exchanges are limited by other considerations to 10,000 lines. Actual experience in Leeds shows that the fears expressed when a five figure exchange was opened were unnecessary, and there has been no appreciable difficulty in this connection. As a matter of fact, when numbers consist of four or five figures a subscriber trusts to his memory for very few numbers, but generally has a handy list of the numbers most in use, and refers to the directory for those only required occasionally. This experience leads one to doubt whether the difficulties in operating six-figure numbers would be so great as are sometimes feared, but the authors are probably correct in thinking that advantage would be derived from giving names to the areas and so reducing the number of figures from six to five. The time seems to have arrived for a revision of the tariff, and the suggestion of the authors to charge upon a unit basis appears an attractive one. It is as desirable for the telephone administration to find as level a load as possible as it is for the electric power authority to do so, and the increased charges during the busy hour and reduced charges during the slack portions of the day would be of great value in this way. Although subscribers would naturally object to any increased charges, they would readily appreciate the loss of service, and they would, moreover, be more willing to pay increased charges for an automatic service than for a manual one as soon as they found the saving of time in making and answering calls, as well as in disconnecting the circuit and making fresh calls, and the reduction in the number of errors of connection, which are obtained by the use of the automatic system.

Bt. Lieut.-Colonel W. A. J. O'Meara (*communicated*): When I had read the powerful arguments advanced in the paper in favour of a general adoption of the automatic system, I began to wonder whether some mistake might not have been made in the dating of the paper, whether indeed 1919 had not been printed thereon in error for 1900. My remarks are not in any way intended as a reflection on the authors; I only call attention to the matter as it was in the year last mentioned that I paid a visit to Canada and the United States of America and had the advantage of hearing the important case of Automatic versus Manual, even at that date by no means a new question, argued by very able counsel on both sides. I was fortunate during my said visit to the North American Continent in seeing and investigating, at various centres, types of two full automatic systems and one semi-automatic system in operation under practical conditions on a considerable scale—the two largest examples of the automatic seen by me were at San Francisco (with 35,000 subscribers' stations) and at Los Angeles (with 23,000 subscribers' stations). I also saw, at an exhibition, the plant designed for the purposes of two other automatic systems. Looking back at the notes that I made at that period, I find that at the date of my visit 72 automatic exchanges had already been completed in Canada and the United States of America and seven more were under construction—total number of subscribers' stations approximately 200,000. I left America carrying away the conviction that it was possible to manufacture and install automatic and semi-automatic equipments which were mechanically and electrically already so reliable as to provide an efficient self-operated telephone service: this opinion was conveyed by me on my return to London, to those in whose hands lay the decisions in relation to the telephone services of the British Isles. Subsequent to 1909, and before the outbreak of the war, I saw further automatic and semi-automatic equipments in operation in Holland, Sweden and Germany—the majority of these were of the same types as those which I had already seen in America, but improved in many details—and I had the opportunity of once more discussing the automatic situation; this time with many able Continental telephone engineers—the majority of them were firmly of opinion that the use of automatic equipments must spread and would eventually completely supplant the manual system. That the introduction of automatic plants has made such slow progress in this country is alone attributable, I fear, to the fact that the telephone service has fallen into the withering grasp of a State Department in which every problem, however technical or scientific, is looked upon as a purely administrative matter; one in which good has always been held the enemy of best. If the public is to wait until the most perfect automatic equipment is invented and designed before the introduction of automatic exchanges is seriously taken in hand in this country, and particularly in London, there will indeed be room for many further papers dealing with the superior merits of the automatic system as compared

with the manual system, for a very considerable number of years, aye for half a century or even a full century to come, since improvements are continually being made in the original types of automatic equipment and entirely new systems are still being invented. Only a few days ago I was privileged to see a private branch exchange in operation in Australia House, where one of the latest automatic systems has recently been installed; I need hardly say, not by the General Post Office. Many telephone users, both in the metropolis and in the provinces, have, in recent times, expressed to me their preference for automatic telephones; they have intimated also that they would be prepared to pay increased rates if thereby they could procure a more satisfactory telephone service than that with which they have had to put up during the past half a dozen years. I may also state that many telephone users, when discussing the situation, have shown considerable irritation owing to the attitude taken up by Government officials imputing a lack of intelligence to the public, who are supposed by them to be incapable of pronouncing any opinion of real value on the relative merits of the rival systems of telephony—manual and automatic. The public are nowadays, as most people are aware, very wide awake and have many and ample means of obtaining reliable information in relation to all technical matters which affect their business or professional interests; to ignore this fact is to bury one's head in the sand. Now there is really no insuperable difficulty in providing a telephone service, even in so large an extent of territory as the present London telephone area, completely by means of automatic equipments, as the authors of the paper clearly show. I do not propose to discuss here the question of the desirability or otherwise of retaining the present London telephone area. It is by no means essential that the contracts for the whole of the automatic equipment required for London should be let to one single firm of manufacturers. I have sufficient knowledge of and confidence in British telephone engineers and manufacturers of telephone equipments to predict that methods of intercommunication between the various practical automatic systems could be satisfactorily worked out by them, as commercial propositions, were they called upon to do so. The question of turning over the telephone service of London to the automatic system is, as the authors point out, largely a financial one, and they have indicated directions in which savings can be effected on the traffic side to compensate for the higher cost of the automatic equipment; but it seems to me that, strong as is their case, they might have made it stronger still. They have assumed, for the purposes of their study of the problem relating to London, that the proposed automatic equipments to replace the present manual equipments are to be installed, in every case, in the existing telephone exchange buildings. If and when the solution of the problem is taken in hand it is needless to say that, for practical reasons, the automatic equipments will have to be housed on sites other than those now in use. This is fortunate, for it affords an opportunity for taking advantage of the peculiar feature of the automatic system, namely, that the grouping of the exchange equipment connected with the subscribers' lines is in no way limited by considerations affecting operators' positions and the design of a switchboard based on the operator's reach. For this reason it would no longer be necessary to adhere to the unit exchange of 10,000 lines hitherto adopted in the case of the manual system. It is evident that advantages arise, in congested areas, from the grouping of as many subscribers' lines as possible at a single point. The present-day methods of fireproof construction in buildings would seem to justify the adoption, in favourable cases, of a new unit, in the case of automatic exchanges, of 50,000 lines. In the United States of America, in some important towns three 10,000 line manual exchanges have in the past been installed in a single building, and, as is well known, in the exceptional case of Hamburg a single exchange was built for and accommodates 80,000 subscribers' lines on the manual system. The 50,000 line unit exchange would admit of a more profitable utilization of the building site than is the case under present practice—thus reducing the charges in respect of rent per line—and would, at the same time, afford an opportunity for a more advantageous grouping of junction lines—thus reducing the expenditure in respect of this item—a matter requiring close attention in view of the very high percentage of the junction traffic in the London area under existing arrangements. Further, with the larger unit exchanges the cost of engineering supervision would be reduced, although *per contra* the cost of the substation line plant would be slightly increased. I venture to suggest that the method of locating telephone exchanges almost exclusively in relation to the distribution of substations is quite unsound in the cases of exceptionally large telephone areas, where a considerable number of separate exchanges must necessarily be provided. It seems to me that the proper way of dealing with the problem in such cases is to examine the situation in relation both to the junction lines needed and to the distribution of the substations. The correct solution of the problem can alone be arrived at by the preparation of two or more complete lay-out schemes for the whole area involved and by figuring out the full costs of each scheme in respect of land and buildings, exchange and substation equipment, junction and substation line plant. When this is done the annual charges for interest on capital, depreciation, materials and stores, heating, lighting, salaries and wages of administrative, traffic and engineering staffs, etc., in respect of each scheme can be ascertained and the necessary data obtained to show which of the schemes is the most profitable from the financial point of view. It is probable that the most advantageous scheme would be found to be one in which the automatic exchanges are located at important intersections of main thoroughfares: such a location of the exchanges would allow of junction lines being laid on the most direct and shortest routes between the several exchanges. The present situation in London cannot be considered satisfactory: it is the legacy of an unfortunate Government policy. Fig. 1 shows that there are at the present time in the Inner London area 20 manual exchanges north of the Thames and 10 similar exchanges south of the river. A very

cursory examination of the plan leads me to believe that the situation of 1920 A.D. in Inner London could be satisfactorily met by the provision of 10 automatic exchanges of 50,000 lines each north of the Thames and four automatic exchanges of 25,000 lines each south of the river. These 14 exchanges could also probably economically accommodate many of the subscribers' lines in the territory adjacent to, but outside, the Inner London boundary marked on the plan (Fig. 1). I confess that the proposed unit of telephone service on page 166 does not appeal to me; the introduction of a time rate in relation to local calls brings into existence a very undesirable element of uncertainty as to one's liability in respect of the cost of the telephone service. It must be remembered that the originator of the call has to pay, but the duration of the call may be entirely dependent upon the fancy of the person called. I agree, however, that with the development in and extension of the use of automatic telephones the present tariff rates should be recast. The value of a local telephone service depends to a large extent on the number of subscribers with whom a telephone user can communicate in return for the fixed sum he is called upon to pay for a block of local calls. The tariff scheme which would most appeal to the small telephone users and which, it seems to me, would best meet the public convenience from all points of view, would be one which was so elastic as to permit the subscribers to pay for their blocks of local calls at rates varying in relation to the facilities placed at their disposal. For example, if the London telephone area were to be divided into regions of, say, 50,000 substations each, a subscriber might be permitted to pay at various fixed rates for blocks of local calls either for originated calls exclusively to subscribers in his own region, or for originated calls to subscribers in one or more regions in addition to that in which his own substation was situated. Every subscriber would naturally under such a scheme obtain any services additional to those provided for by the fixed rates on payment of the appropriate junction call fees, etc. In conclusion, I sincerely hope that the paper will bear fruit. The question of providing London with a telephone service on the automatic system is a pressing one, and a complete investigation of the problems involved is of immediate importance; admittedly there are *cons* as well as *pros* to be taken into account. It would seem to be the function of the administrative and traffic staffs of the State Telephone Service to put forward arguments against the automatic system, and it would then fall to the technical staff to meet the objections raised. This done, it would eventually be for the Minister responsible for our telephone services to determine whether the case for automatic telephones had "proved in." Should he require assistance to decide the point, there are available, fortunately, competent telephone experts who are not, and who have never been, in the State Service; they could easily be empanelled as a jury and could be relied upon to return a just and true verdict.

Mr. P. G. Pettifor (*communicated*): The telephone unit system of charging referred to by the authors would be an improvement on the present method of charging, even although the meters were located at the exchange, but it would undoubtedly be a great advantage from the subscriber's point of view to locate the meter on his premises. The electric light user referred to by the authors has some consolation in having the meter on his premises, inasmuch that he can, if he so desires, check his consumption day by day. I would suggest that in any re-numbering of subscribers' lines that may take place, certain terminal digits should be allocated to the public service, such as "Fire, Ambulance," etc., with the eventual idea of uniformity of such digits throughout the Kingdom. Speaking as one engaged on the manufacturing side, I should like to emphasize a point referred to by the authors, regarding the capital costs of automatic equipments. Such costs can only be brought down by the Authorities ordering equipments of standardized type in such numbers as will induce the manufacturers to lay themselves out for the work. This is a new branch of industry in this country, and it is an excellent opportunity for it to be started on the right lines.

Messrs. **E. A. Laidlaw** and **W. H. Grinsted** (*in reply, communicated*): We attempted to bring forward in our paper in as broad as possible a manner the changes which have been brought about by the war in the main factors of the provision of telephone service in large cities. We dealt with the matter on a broad engineering basis, and tried to avoid any reference to particular systems of manual or of mechanical switching, and any mention of matters proper only to the administration, and of commercial or technical questions affecting only particular manufacturers. We feel that we should use the same discretion in replying to the discussion, and so do not propose to deal with those contributions which introduce matters related to the capabilities of different manufacturing firms, the alleged shortcomings of the present tariffs and service, and the policy of the General Post Office.

Among the matters coming within the scope of the paper, Mr. Hedley and Mr. Anson confirmed and amplified the figures given showing the improved quality of service afforded by the automatic system. These results, based upon the careful service observations of the Post Office, as well as Mr. Baldwin's general remarks upon the same subject, strongly support our statements. Mr. Cook emphasizes the importance of service observations and fears that sufficient attention is not being directed to this question. Even if the numerous figures relating to automatic equipments given in the paper were not sufficient to indicate the attention which is being paid to service observation, we think Mr. Anson's and Mr. Hedley's remarks show that the Post Office are fully alive to its importance.

Mr. Ward commented on our remarks with regard to the desirability of increasing the exchange voltage, and quoted an example from his experience, which tended to show that a lower insulation was experienced on wires maintained at 60 volts than on those maintained at 30 volts. Our experience does not confirm Mr. Ward's in this respect. We do not know whether he has any explanation to offer of the difference noticed by him. Possibly it may lie in the polarity of the two lines: if both were negative, the conductor at the lower (more negative) potential might be expected to show

a lower insulation to earth. The following figures are summarized data collected from nine representative exchanges, totalling nearly 16,000 lines :—

Percentage Number of Lines having an Insulation Resistance between the Wires of the Loop.

	Less than 0·5 Megohm	Less than 0·4 Megohm	Less than 0·3 Megohm	Less than 0·2 Megohm	Less than 0·1 Megohm	Less than 0·06 Megohm
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
6 24-volt Exchanges	28	22·4	17	10·5	6	2
3 36-volt Exchanges	31·5	9·7	7·1	4·5	2·6	1

Questions of tariffs and metering were touched on by several speakers. We should perhaps have made it clearer that the device we have in mind for including the time element in recording the service rendered to a subscriber is a simple apparatus based upon electro-chemical principles, the record depending upon the time it is in circuit and the strength of the current, which is regulated according to the rate at which the call is to be charged. We think, therefore, it is not open to the objection of complication raised by Mr. Anson and Mr. Aitken. It seems probable that the general adoption of automatic working will call for some change in the basis of the tariffs. The return to the flat rate proposed by Mr. Aitken certainly demands some restriction on the number of calls passed over one line. For this reason we are inclined to think that neither the flat rate nor the restricted service measured rate outlined by Colonel O'Meara will prove to be the ultimate scheme. The soundest and most businesslike principle from the commercial, economical and technical points of view, seems to us to be to offer the public every facility for making use of the telephone service and charge them according to the use they make of it. The flat rate asks the subscriber to pay according to the facilities provided rather than according to the use he makes of them. A restricted measured rate restricts the facilities offered and, if graded according to the range over which the fixed rates apply, also requires payment according to the facilities rather than according to the use made of them. Obviously, there is a limit to the application of this principle—the minimum charge made must be sufficient to provide a reasonable return on the capital expenditure involved in providing the facilities offered the subscriber. The reduction in rates for the slack periods of the day suggested in connection with the " unit of telephone service " would, we think, appeal at least as strongly to the small user as the restricted service outlined by Colonel O'Meara. We do not think his objection that the charge would depend entirely upon the fancy of the person called would be serious, as the calling subscriber can clear the connection at any time and so cause the meter to cease recording.

Several members referred to the desire to have the meter at the subscriber's end of the line. This is an ideal which we are afraid will never be realized, on account of the technical difficulties which stand in the way as long as only a pair of wires can be provided for each line.

Several speakers commented on the financial aspect. Mr. Kingsbury and Mr. Cook were anxious lest the Administration should embark on the general introduction of automatic working without a carefully prepared estimate of the costs. We do not think they need have any fear of a Government Department doing anything so rash. We appreciate and made it clear that such an estimate would have to be prepared, although, as they both agree, it was impossible for us to undertake its preparation and presentation in the paper. With regard to the high first cost of automatic equipment, of which Mr. Cook complained, the most effective way of bringing about a reduction is through an increase in production. A manufacturer has not, as Mr. Cook implied, any particular wish to bring about the adoption of automatic working. He is quite content as a manufacturer to supply what is demanded, at the same time keeping watch on current tendencies so that he may be in a position to meet altered demands in the future. Mr. Pettifor's remark that the cost can only be brought down by the Authorities ordering standardized equipments in sufficient numbers to induce manufacturers to lay themselves out for the work, illustrates the manufacturer's standpoint.

Even the financial comparison, however, is not the sole deciding factor. An administration dare not continue on a course, although estimates show it to be financially advantageous, if the trend of events is such that it is obvious that this course will have to be abandoned in the near future on account of the growth of the undertaking, the public demand for a superior service, or for other reasons. In such a case it is proper for administrations to meet the increased charges incurred in adopting the more progressive scheme by an increase of the rates. Mr. Johnson and other speakers gave it as their opinion that the subscribers would raise no objection to an increase for such a reason. In our opinion, and apparently Mr. Anson and Mr. Johnson agree with us, the introduction of automatic working is likely to prove to be an illustration of this point, for it seems very doubtful indeed whether the manual system is capable of meeting the requirements of, say, 10 years ahead, and 10 years is a short period where the conversion of the telephone system of a large city is concerned.

It was this feeling which caused us to introduce the argument about which Sir William Slingo wished to cross swords with us, namely, that the rate of depreciation adopted for manual plant should be increased in

view of its approaching obsolescence. Possibly we did not make our point as clear as we might have done. It is not a question, as Sir William puts it, of shortening the life of existing manual plants to get an increased depreciation account to pay for the automatic. What we have in mind is a case in which the two alternatives, manual and automatic, are being compared for new work. Ten years ago there would have been no question that the rate of depreciation for the manual equipment, taken in the comparison, could have been based upon its properly estimated economic life. At the present date, however, owing to the tendencies discussed in our paper, and the doubt whether manual plant is capable of meeting the requirements of the near future, it would be a wise precaution to allow for a shorter life for the new manual plant than would have been allowed 10 years ago. To borrow an illustration from life insurance, in fixing the depreciation for a manual system now we are insuring a "bad life," and the premium for new risks undertaken in this class of business should be higher than they were when manual plants were "good lives" Unless some such precaution is taken, the depreciation account will be inadequate when the events happen which we and all the speakers agree to be imminent. This will be a serious situation and one which should have been foreseen and provided against.

Dealing with the section headed "Technical Problems of Automatic Systems in Large Cities," several speakers referred to the numbering scheme. It is remarkable how the objections to the use of numbers with more than four digits, or more generally speaking, of designations with more than four symbols, have disappeared. Both Sir William Slingo and Mr. Johnson have testified to the satisfactory experience with five digits at Leeds, and Mr. Kingsbury agrees that for automatic operation we may give way to the necessities of the situation and adopt a four-, five-, or six-digit number. This emboldens us to suggest as the way out of the difficulty he raises due to the number of subscribers growing beyond the allowance:—Why not a seven-symbol number? This would make it possible to allot 100,000 numbers where we have allotted only 10,000, and for the case he quotes, viz. Merstham, 10,000 numbers where the ultimate is 422 lines. The possibility of the allowance of numbers being exceeded then becomes negligible. He suggests that the carrying out of a scheme for London would be facilitated by reducing the size of the London telephone area. The difficulty is to decide where to make a division which would be effective and yet not involve an economically unmanageable volume of cross-boundary traffic. Mr Preece suggested letters throughout instead of numbers. We doubt very much whether subscribers would appreciate the weird code words which would result. Any combination of numbers makes sense; most combinations of letters make nonsense. Mr. Anson's suggestion to arrange the numbering scheme in such a way that an exchange code can be substituted for, and dialled as, the first two symbols, is an ingenious method of meeting the number-changing difficulty and, further developed to give greater flexibility, might lead to a scheme which is almost ideal, namely, one in which existing exchange names and numbers might be retained to a very large extent. We doubt, however, whether it would be possible to find 10 letters from which codes representing the existing exchange names could be made up; probably it would be necessary to assign more than one letter to each space on the dial. Further, if the seven-symbol number were adopted, three letters would be required for the exchange code in order that the existing four-figure number might be retained. This would mean assigning possibly three letters to each space on the dial, and a practical difficulty then crops up, for the space is restricted and it would not be easy, particularly for persons with bad sight, to pick out the letters. With the regional name as proposed by us, or a single letter, it would be possible to remember the positions of the names or letters on the dial, and further, the names or letters would be more easily recognizable with bad light or poor sight. Experience only will show which scheme will prove to be the most advantageous, but we feel that an exchange code scheme, although it presents advantages for the transition period, will not be the most satisfactory for the ultimate conditions. Perhaps we are too revolutionary in desiring to adopt at once what seems to be the best for those conditions; but even with an exchange code scheme, we still think it would be desirable to change all directory entries at once, some time prior to the opening of the first automatic exchange, in order that all subscribers, those remaining manual as well as those becoming automatic, might become acquainted with the new designations. No matter what scheme is adopted, the numbers in the first thousand must be changed or prefixed with zeros, and number-changing due to re-arrangement of the areas to obtain the maximum economy from the automatic system will always be necessary. It seems to us far more desirable to effect as much as possible of this number-changing prior to the introduction of the automatic system. Mr Aitken will notice that the method of private-branch-exchange operating which we propose does not involve the dialling of seven, eight, or nine figures. The practice of dividing the number into syllables as he mentions has been in general use in France, even on manual equipments, and is undoubtedly helpful. We think the registering device he proposes will not be found necessary or very acceptable by subscribers.

Colonel Ogilvie commented on the increase in junction plant necessary if junction groups are limited to 10 lines. There is no reason why they should be limited to 10. There are several methods developed and others in the course of development which overcome this difficulty. This also replies to Mr. Hedley's inquiry regarding large groups of private-battery-exchange lines. He also referred to the service difficulties and expense likely to be incurred during the transition period. In our opinion there is no doubt whatever that these difficulties and expenses will have to be faced, and, as we have pointed out in the paper, there is never likely to be a better opportunity than now. Certainly, the longer they are put off, the larger they will become.

Mr. Hedley asked for more details concerning the metering of intimator calls. These are to all intents and purposes automatic calls and can be metered automatically in the same way as a completely automatic

call, i.e. depending upon the called subscriber's reply. He also suggested that with the scheme advocated by us for dealing with manual to automatic calls, a line might be picked up by a switch during the period which elapses between the operator testing and plugging in; this period is extremely short. The manual system is open to the same possibility of another "B" operator plugging in during this period, but no practical difficulty is experienced. The great advantage of scheme 3 is that it uses up available replaced plant and avoids the purchase of a very large quantity of new plant of a special nature which will only be in use for the transition period. With regard to the change in subscribers' numbers, we cannot agree that the difficulties or the risk of changing numbers twice will be any greater with a well-thought-out scheme applied as a whole than with piecemeal changes spread over the whole of the transition period.

A DEVICE FOR THE RAPID DETERMINATION OF THE CURRENT DISTRIBUTION ON THE LINE SIDE OF A THREE-PHASE INTERCONNECTED-STAR STATIC BALANCER OPERATING ON A FOUR-WIRE SYSTEM.*

By S. Austen Stigant, Associate Member.

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Introduction.

With the increasing necessity for the installation of three-phase interconnected-star static balancers supplying unbalanced single-phase loads from line to neutral, it naturally becomes of more frequent necessity to determine the current distribution on the line side of the balancer in order to ascertain whether or not existing cables will be capable of carrying any additional contemplated load. The purpose of this communication is to describe a device which will facilitate the determination of the line currents under different loading conditions and so render the complete operation of but a few minutes' duration.

Completely to illustrate the principles upon which the device is based, graphical solutions are included.

Conditions of Loading.

The loads supplied (which are throughout assumed to be at unity power factor) may be any of the following, as shown in Fig. 1:—

(*a*) One single-phase load only from one line to neutral.
(*b*) Two single-phase loads from lines to neutral, which loads may be either equal or unequal.
(*c*) Three single-phase loads from each line to neutral, which loads may be either all equal or all unequal.

Case (*a*).—The top diagram in Fig. 1 illustrates case (*a*) where an assumed load of 100 amperes is supplied. As the load is single-phase, arithmetical quantities only have to be dealt with.

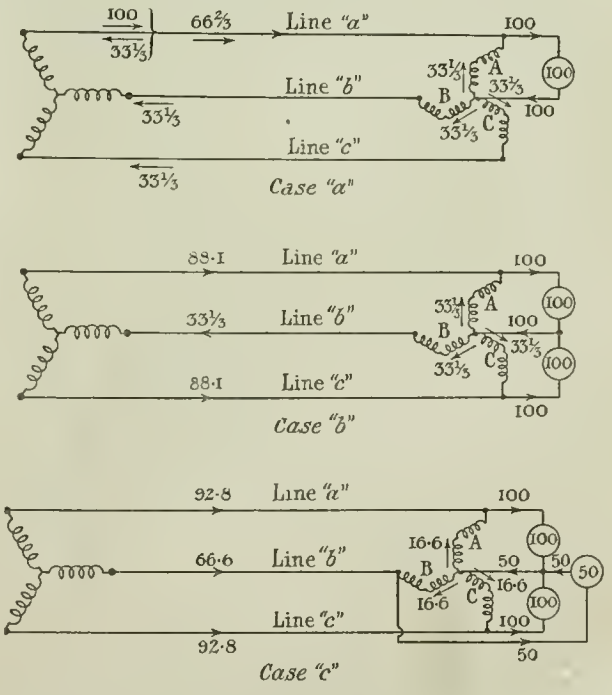

Fig. 1.

The problem can most easily be handled by assuming, to commence with, that the outgoing full-load current of 100 amperes traverses line *a*, passing on to the

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load to be supplied. The neutral wire carries the full value of the load current, which latter divides up, on reaching the neutral point of the balancer, into $33\frac{1}{3}$ amperes in each phase winding and returns to the generator in equal amounts through the three line-wires *a*, *b*, and *c*. Line *a*, however,

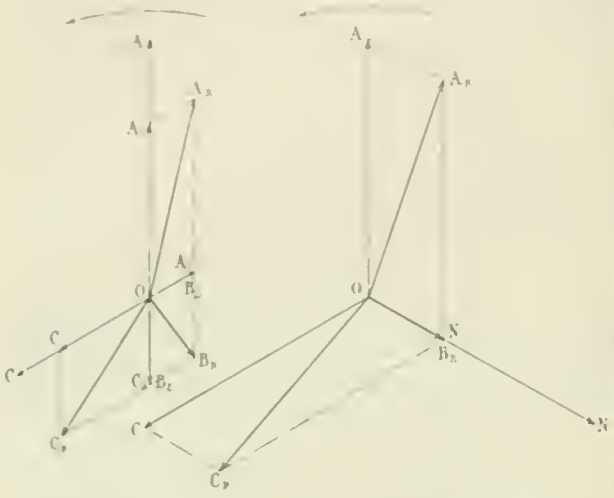

FIG. 2A.

FIG. 2B.

already carries 100 amperes in an opposite direction, so that the net result in this line is $100-33\frac{1}{3}=66\frac{2}{3}$ amperes. The other two lines each carry $33\frac{1}{3}$ amperes. With one single-phase load this ratio between the actual currents in the three lines always remains the same, i.e. in the line from which the load is connected both of which are, however, closely allied. The one is to treat each load separately throughout the entire circuit, knowing from the method indicated in case (*a*) the proportion of current carried by the non-loaded phases in each case, and to combine the currents vectorially (in each line wire) which result from the two loads. The neutral current must then be found separately, by vector addition of the separate load currents which flow in the neutral wire. This is the method upon which the current-calculating device is based.

The other method is first to find the neutral current as above and vectorially combine one-third of this with each of the normal full-load currents in the three line-wires, *a*, *b*, and *c*. The results obtained are identical.

Figs. 2A and 2B illustrate the two methods; in Fig. 2A the load currents are assumed to be unequal, 100 and 60 amperes respectively, while in Fig. 2B they are taken as being 100 amperes each.

It will be noticed that in the case of equal loads the neutral current is of the same value as the currents on the load side of the balancer and displaced 120° from each of them; the currents in the line wires *a*, *b*, and *c*, bear the fixed ratios to one another of 88·1 per cent in each of the two loaded phases and $33\frac{1}{3}$ per cent in the unloaded phase. These percentages are in terms of the current in each load.

Relative maximum loading of the neutral wire (and also of the balancer) occurs with either one load only from line to neutral or with two equal loads.

As case (*c*) offers more scope for explanations of the vector diagrams, case (*b*) is not dealt with in detail. Precisely the same remarks apply in general as for case (*c*).

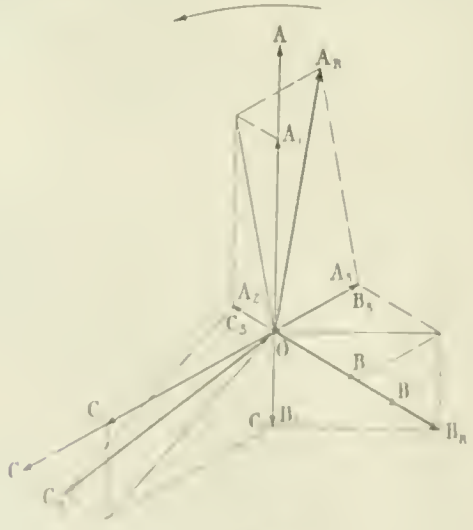

FIG. 3A.

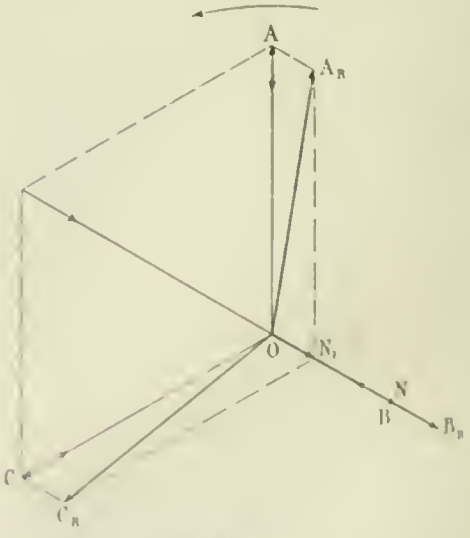

FIG. 3B.

to the neutral $66\frac{2}{3}$ per cent and in each of the other two lines $33\frac{1}{3}$ per cent of the normal full-load current. This detail is, of course, not necessary for this case, it being only inserted to indicate the method upon which the subsequent graphical solutions are based.

Case (c).—There are two different methods to adopt,

Case (c).—Figs. 3A and 3B show the two methods previously referred to. In the first method, Fig. 3A (upon which the device is based), we will follow the complete path of each load current separately, and assume the currents on the load side of the balancer to be: phase A = 100 amperes, phase B = 50 amperes,

and phase C = 100 amperes. These currents are represented by O A, O B, and O C respectively, in the vector diagram, being in phase with the voltage to the neutral in each case and therefore spaced 120° apart.

Then, due to the load across phase A, the current in line *a* is equal to two-thirds of O A and is represented by O A_1, while the currents in lines *b* and *c* equal one-third of O A and, flowing in opposite direction to O A_1, are represented by O B_2 and O C_2. Due to the load across phase B the current in line *b* equals two-thirds of O B and is represented by O B_1, and in lines *a* and *c* the current equals one-third of O B and is represented by O A_2 and O C_3. Similarly with phase C the current in line *c* due to its load is represented by O C_1, and in lines *a* and *b* by O A_3 and O B_3 respectively.

Tabulated, the currents so far involved are :—

In line wire a.

O A_1=66·66 amperes,
O A_2=16·66 ,, , leading O A_1 by 60°.
O A_3=33·33 ,, , lagging O A_1 by 60°.

In line wire b.

O B_1=33·33 amperes,
O B_2=33·33 ,, , lagging O B_1 by 60°.
O B_3=33·33 ,, , leading O B_1 by 60°.

In line wire c.

O C_1=66·66 amperes,
O C_2=33·33 ,, , leading O C_1 by 60°.
O C_3=16·66 ,, , lagging O C_1 by 60°.

Combining O A_1, O A_2 and O A_3 as shown, gives O A_R which scaled *=93·0.
Combining O B_1, O B_2 and O B_3 as shown, gives O B_R which scaled =66·6
Combining O C_1, O C_2 and O C_3 as shown, gives O C_R which scaled =93·0.

$\cos\theta_A$=0·987 ; $\cos\theta_B$=1 ; $\cos\theta_C$=0·987 scaled.*

The neutral current is obtained in a similar manner by adding vectorially the three load currents O A, O B and O C assumed to be flowing towards the neutral point. The value so obtained is represented by O N as shown in Fig. 3B, and equals 50 amperes. In the second graphical method, Fig. 3B, the neutral current is first determined as above. This current on reaching the neutral point of the balancer divides up into one-third of its value in each phase, being represented by O N_1, and flows back along lines *a*, *b* and *c*. In this case the actual current in line *a* is the resultant of O A and O N_1 which, as in the previous graphical case, is represented by O A_R. Similarly O B_R is the resultant of O B and O N_1 while O C_R is the resultant of O C and O N_1.

The Device.

As the relative quantities, and consequently the scales involved in the determination of the line and neutral currents, are somewhat different, to avoid possible confusion the device has been made double-sided, the one side determining line currents and the other the neutral current.

Fig. 4A shows the former and Fig. 4B the latter.

The aim throughout has been to design the device so that the values dealt with are the normal load currents only and entirely to eliminate the introduction of all confusing factors, such as sines and cosines of angles and fractions of the load currents as are involved in the mathematical and graphical analysis.

Line currents. Construction.—The current in each line *a*, *b* and *c*, is determined separately by means of the three sets of scales forming the "star" clock diagram, each of which scales extend beyond the neutral point. Decide first the range of load currents with which the device must deal, describing a circle, with the maximum value settled upon, to some suitable scale, as radius. That shown has a maximum range of 100 amperes and was originally constructed so that 10 amperes=1 cm., i.e. the circle was of 10 cm. radius. Lay out three equally spaced (120° apart) radial lines, viz. A, B, C, in the key diagram Fig. 5A, and extend these lines one-third of the radius in length beyond the centre or neutral point. As the three sets of scales subsequently built up on lines A, B, and C are identical, the following remarks describe one of them (for phase A) only.

On the left-hand side of line A set out the scale (*d*) of load currents previously decided upon, the centre of the circle being zero. On the same side of the line but below the centre construct a similarly graduated scale (*e*) which will give a maximum reading of one-third of scale (*d*). On the other side of line A and adjacent to scale (*d*) construct a scale (*f*) equal in length from the centre outwards to two-thirds the length of (*d*), but graduated to give the same maximum reading. Referring to the device originally constructed by the author, this scale (*f*) was consequently drawn 6·66 cm. in length, 15 amperes=1 cm. On the same side of line A but below the centre draw the scale (*g*) adjacent to (*e*) and so graduated as to give a maximum reading of six times that of scale (*e*), though in actual length (*g*) and (*e*) are the same, viz. one-third of the radius. Assuming these four scales to have all been constructed on each of the three radial lines A, B, and C (Fig. 5A), the next step is to project a series of parallel lines running from each division and on either side of scale (*e*) to the circle touching the extremities of scales (*d*). These series of lines are drawn parallel to the two remaining radial lines, i.e. in the case of the (*e*) scale of phase A the series of lines are drawn parallel to lines B and C as indicated at (*h*) and (h_1). These scales are marked round the circle periphery to embrace the same maximum readings on either side of the radial lines A, B, and C, as scale (*d*) ; the zero being at the intersection of lines A, B and C with the circle. The scales are further marked with the letters A, B or C as indicated on the completed drawing. The final scales (*k*) to be drawn are simply horizontal extensions of all divisions of the (*d*) scales to the boundaries of the (*h*) and (h_1) scales on both sides. The line-current side of the device is then completed by inserting the scale of power factors as shown and by providing a strip of transparent celluloid (Fig. 5B) pivoted at the centre of the device and of a length to reach the power-factor scale. The strip is provided with a scale marked exactly the same as scale (*d*).

When constructing this device the author has found

* The vector diagram being set out inside a 6-inch diameter circle.

that scales (h), (h_1) and (h_2) are clearer if drawn in red, the main divisions only (every tenth) being lined in in black. It is also an advantage to number and letter scales (h) and (h_1) in red as they do not then become confused with the power-factor scales.

Explanation.—All subsequent scales are based on scale (d), Fig. 5A, this scale being set out to embrace central vector. That is, the current in line a is the vectorial sum of OA_1 (the central vector), OA_2 and OA_3. The total power component is therefore

$$OA_1 + \cos 60^\circ\ (OA_2 + OA_3) = OA_1 + \tfrac{1}{2}\ (OA_2 + OA_3)$$

OA_1, OA_2 and OA_3 are certain proportions of the respective load currents OA, OB and OC, but as it

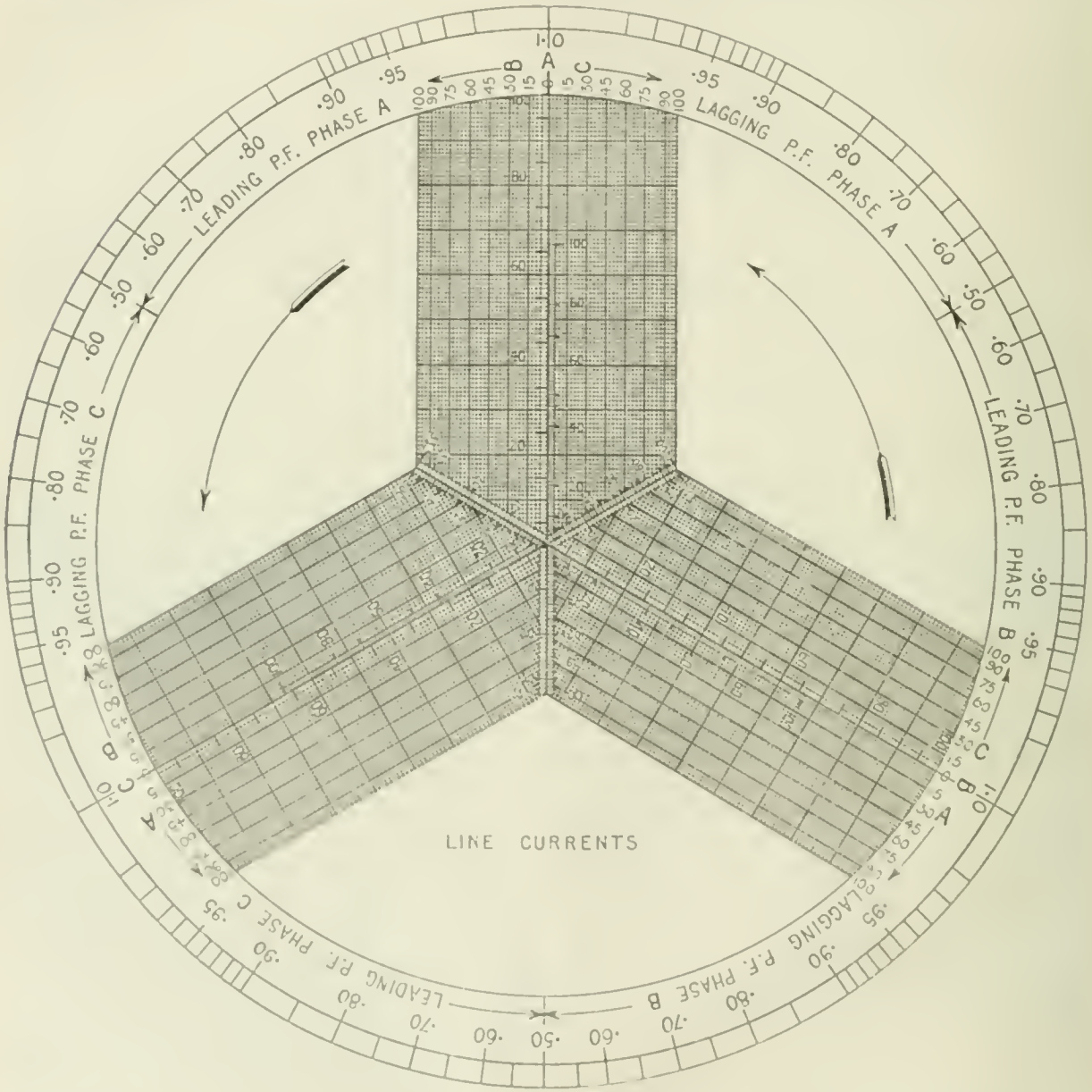

FIG. 4A

is only desired to deal with the full values of load currents when using the device, it is simply a matter of choosing a suitable scale whereby fractions may be eliminated.

Now OA_1 is two-thirds the value of the load current OA, so that if scale (f) is drawn adjacent to and two-thirds the length of (d), but marked to embrace the same maximum value as (d), we can immediately read

off on (*d*), by transferring the value of O A across from (*f*), the true value O A_1. Now O A_2 and O A_3 (Fig. 3A) cannot exceed one-third the value of their respective load currents O B and O C, and consequently the length of scale (*g*) required to accommodate these values will be $\frac{1}{2}(\frac{1}{3}+\frac{1}{3})$=one-third the length of scale (*d*), for the power components being in phase one scale up to a maximum of one-third the value of (*d*), the true power components of O A_2+O A_3 can be read off on (*e*) opposite the value of O B+O C on (*g*). If the value so obtained be added to that previously obtained on scale (*d*) from (*f*), the sum of the total power components is determined for that particular line. When dealing with any one line—say *a*—the wattless com-

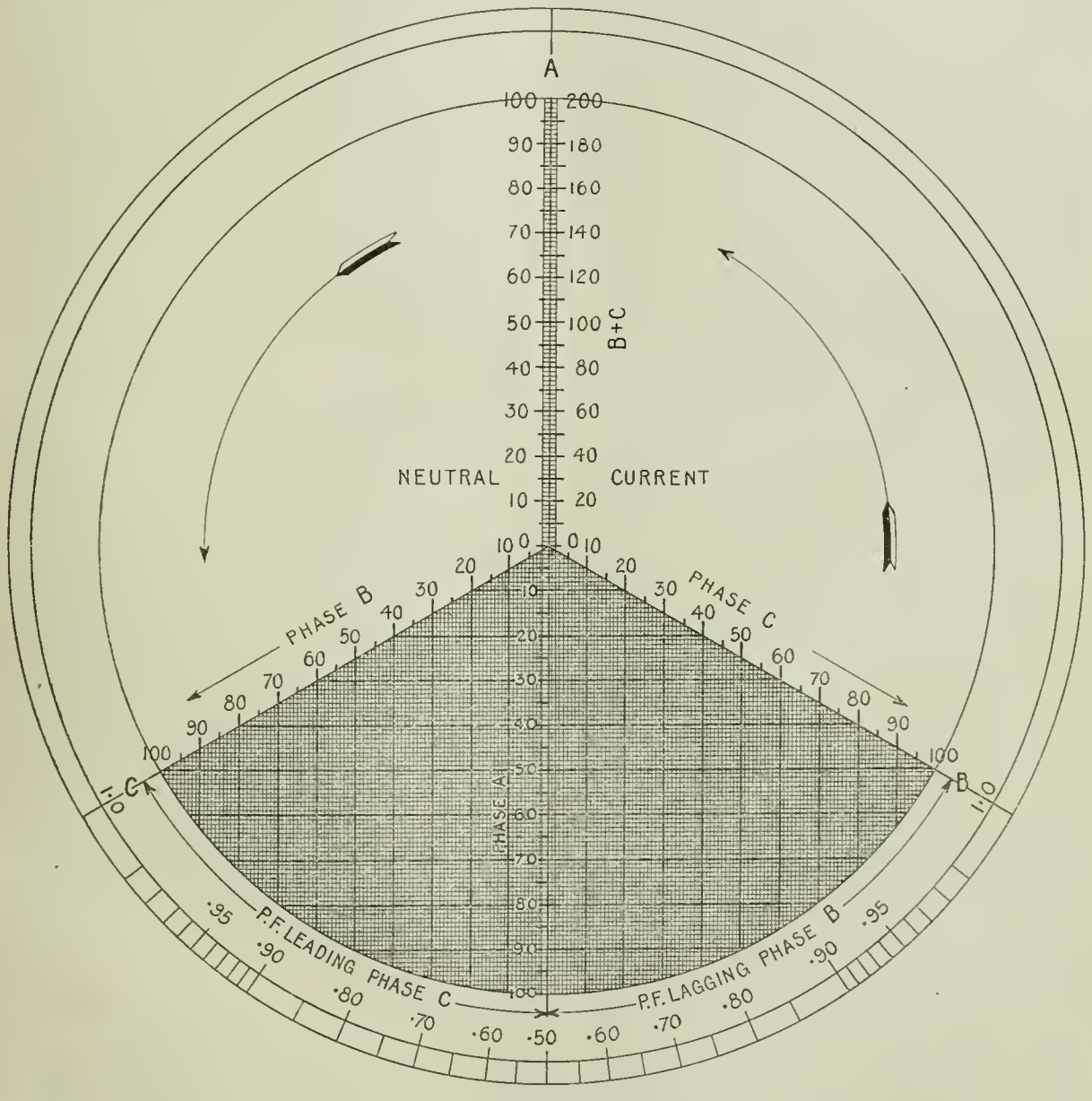

FIG. 4B.

can be used for the sum of the power components of O A_2 and O A_3. The marking of the scale must, however, be such as to give a maximum reading of twice that of scale (*d*), viz. 200 in Fig. 4A, so that only full values of load currents are handled throughout the operation. By drawing scale (*e*) adjacent to (*g*) but to the same scale as (*d*), and in consequence reading

ponents involved are those of the currents from phases B and C only, and as these are reckoned on either side of the scales (*d*) two separate scales (*h*) and (h_1) must be provided for each line which, however, are identical.

These scales should register the same maximum values as scale (*d*).

The horizontal extensions of the (*d*) scales are drawn simply to obtain intersection points with the lines of the (h) and (h_1) scales, which accordingly facilitates the taking of the end of the vector representing the actual current in the line under consideration.

Example. Case (a).—Three separate loads to the neutral having the same values as given for the graphical analysis

A = 100 amperes B = 50 amperes C = 100 amperes.

Line a.—Mark load A = 100 amperes on scale (*f*); then corresponding adjacent reading on scale (*d*) = 66·6 amperes . . . . . (1)

Mark on scale (*g*) loads B + C = 150 amperes; then corresponding adjacent reading on scale (*c*) = 25 amperes . . . . . (2)

Mark on scale (*d*) (1) + (2) = 66·6 + 25 = 91·6 . . (3)

which is the true power component of the current in line *a*. Subtract the smaller from the larger load on the other two phases, i.e. in this case

C − B = 100 − 50 = 50 amperes . . . . (4)

= load on phase C.

Mark this value on scale (h) or (h_1), according as to which phase carries the greater load, and trace downwards until intersection takes place with the horizontal projection of (3).

Rotate the pivoted celluloid strip until the line drawn down the centre lies over the point of intersection, when the true value of the current in line *a* is read off direct on the scale adjacent to the centre line on the strip. The figure is 91 amperes.

The power factor of the current in line *a* is registered also by the centre line on the strip which is extended to meet the power-factor scale. In this case the power factor equals 0·99 lagging, approximately.

Line b.—Mark load B = 50 amperes on scale (*f*); then corresponding adjacent reading on (*d*) = 33·3 amperes . . . . . (5)

Mark on scale (*g*) loads A + C = 200 amperes; then corresponding adjacent reading on (*c*) = 33·3 amperes (6)

Mark on scale (*d*) (5) + (6) = 33·3 + 33·3 = 66·6 amperes . . . . . (7)

which is the true power component of the current in line *b*.

Loads A − C = 100 − 100 = 0 amperes . . (8)

There is therefore no wattless component of the current in line *b*, and the total current equals 66·6 amperes at unity power factor.

Line c.—Exactly as line *a*, except that the power factor is leading.

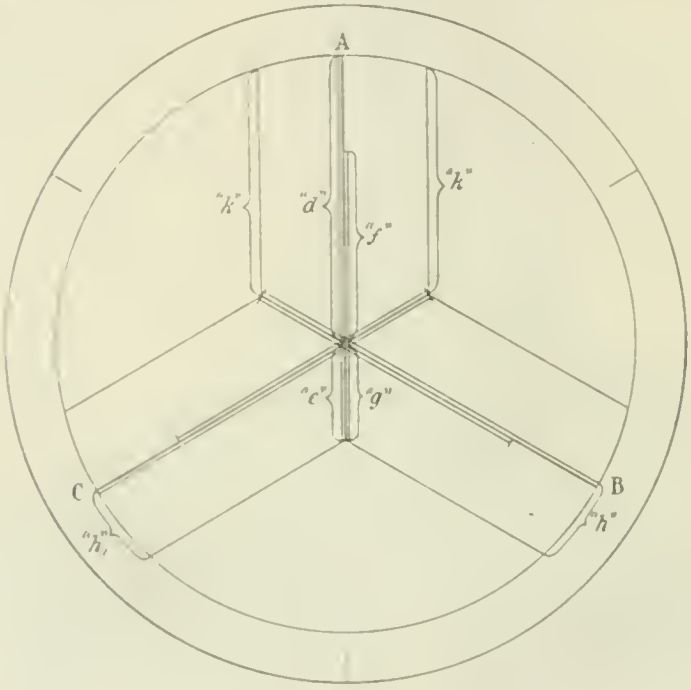

FIG. 5A.

FIG. 5B.

NEUTRAL CURRENT—CONSTRUCTION.

In this case a key diagram is hardly necessary, as the construction is much simpler. As the maximum values provided for are the same as in the case of the line-current side of the device, three similar circles are drawn of the same diameters as in Fig. 4A.

Lay out three equally spaced (120° apart) radial lines, A, B, C; A, however, being extended for the full diameter of the inner circle as shown in Fig. 4B.

On the left-hand side of line A, and both above and below the centre of the diagram, set out the two scales of load currents previously decided upon, the centre

of the circle being zero. These scales will be identical with scale (*d*) of Fig. 5A. On the right-hand side of line A, and above the centre of the diagram, construct the scale marked (B+C) of the same length as the previously drawn adjacent scale, but graduated to give a maximum reading equal to twice the normal load current. On the remaining radial lines, B and C, construct scales identical with those on the left-hand side of line A. The graduations of the scale marked "phase A" in Fig. 4B are extended horizontally on either side, as shown, to the boundaries of the radial lines B and C, and to the inner circle. Similarly those of the scales marked "phase B" and "phase C" are also extended vertically downwards to the periphery of the inner circle. As in the case of the line-current diagram these series of lines present a much clearer result if drawn in red, the main divisions only being lined in in black. The scale of power factors embraced by lines B and C is then inserted, and the diagram finally completed by inserting the figures and lettering shown in Fig. 4B and providing a pivoted strip of transparent celluloid exactly the same as for the line-current side of the device.

Explanation.—As with Fig. 4A, all subsequent scales are based on scale (*d*) of Fig. 5A. Fig. 3B shows the vector construction for determining the actual current flowing in the neutral wire, and it will be seen that the resultant vector of the two phases (A and C in this case) is thrown on to the opposite side of the neutral point to that required, although subsequent subtraction of the current flowing in the neutral wire due to the load on phase B gives the resultant O N in the required position.

Now if the maximum load scale [corresponding to (*d*), Fig. 5A] of phase A were set out on the A vector above the neutral point of the diagram, as for instance in the case of Fig. 4A, the load scales for determining the wattless components of phases B and C would have to be drawn from their respective vectors B and C, parallel to the vector A and upwards to the periphery of the inner circle. As any such scales extending beyond 60° on either side of A would be useless, the B and C scales would each be built up on a radial line terminating midway on the inner circle periphery between A and B, and A and C respectively. The result of this construction would be to obtain a vector for the actual neutral current which would lie in the opposite direction to the true direction. The value indicated by any vector would be quite correct and the true position could also be shown by suitably marking the power-factor scale on either side of A.

If, however, all the scales were set out on vectors radiating in an opposite direction, the true position of the vector representing the actual neutral current would be indicated. The power-factor scales would also be shown in their correct position.

It is this construction that is shown in Fig. 4B. The load scale for phase A is set out on an extension of line A below the neutral point, that for phase B on line C, and that for phase C on line B. The position of the neutral current vector may be determined with respect to either A, B or C. In Fig. 4B, A is chosen as the reference line, and when applying the device A should be the phase supplying the largest load. The scale B+C represents the sum of the power components of the currents in phases B and C (referred to A) in terms of the full-load currents, and must obviously be of the same length as the load scales and give twice the maximum readings, since the maximum possible sum of the wattless components of B and C is equal to the maximum value for which the chart is designed. Transferring the value of B+C to the adjacent scale will give the true value of the sum of the power components for phases B and C. The value so obtained should then be subtracted from the full-load current of phase A, the difference being noted on the scale marked "phase A." This is then the true power component of the neutral current referred to phase A. To ascertain the value and direction of the wattless component, note the difference between the full-load currents of phases B and C, and lay this off on the predominating scale marked "phase B" or "phase C" as the case may be. The intersection of the projections from the value so obtained for the wattless component and the value previously obtained for the power component will give the extremity of the neutral current vector. The line connecting this point with the centre of the chart gives the value of the neutral current to the same scale as the load currents.

Examples. Case (*c*).—First, two separate loads to the neutral having the same values as given in Fig. 2A.

A=100 amperes. B=0 amperes. C=60 amperes.

Mark load A=100 amperes on scale "phase A" . (9).

Mark the sum of the loads B and C=60 on the scale B+C and transfer this value to the adjacent scale, which gives a reading of 30 amperes . . . . . (10)

Subtract this 30 amperes from the value of the load current of phase A, registering the difference, 100−30 =70 amperes, on "phase A" scale . . . . . (11)

This is the power component of the neutral current referred to phase A.

Subtract the smaller from the larger load of phases B and C, in this case 60−0=60 amperes in favour of phase C, and mark this value on "phase C" scale, constructed on the B radial vector . . . . . (12)

Trace downwards until intersection takes place with the horizontal projection of (11), and rotate the pivoted celluloid strip until the line drawn down the centre lies over the point of intersection, when the true value of the neutral current is read off direct on the scale adjacent to the centre line on the strip.

This equals 87 amperes.

The power factor of the neutral current, registered by the centre line on the strip, which in this case also is extended to meet the power-factor scale, is 0·92 approximately, lagging behind the voltage of phase B.

Secondly, two separate loads to the neutral having the same values as given in Fig. 2B.

A=100 amperes. B=0 amperes. C=100 amperes.

Mark load A=100 amperes on scale "phase A" . (13)

Mark the sum of the loads B and C = 100 on the scale B + C, and transfer this value on to the adjacent scale, which gives 50 amperes . . . . . (14)

Subtract (14) from (13) marking the difference 100 − 50 = 50 amperes on "phase A" scale . . . . (15)

Subtract load B from C, i.e. 100 − 0 = 100 amperes in favour of phase C, and mark this value on "phase C" scale as in the previous example . . . . . (16)

Trace downwards till intersection takes place with the horizontal projection of (15), and rotate the pivoted strip until the scale thereon registers the value of the neutral current. This equals 100 amperes and is in phase with the voltage of phase B.

It is appreciated that the construction could be applied to the ordinary type of alignment chart employing one set of scales only, but the circular disc type as illustrated in this paper has the advantage of showing at a glance the relative vector positions of the line and neutral currents and voltages.

ELECTRICAL PHENOMENA OCCURRING AT HIGH LEVELS IN THE ATMOSPHERE.

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1. It is well known that the properties of the atmosphere are different in important respects above and below a fairly well-defined surface of separation, which is usually situated at a height of about 10 or 15 kilometres from the ground. The layer beneath this surface is called the troposphere, and is characterized by the presence of much convective motion; the temperature in this layer consequently diminishes upwards. In the upper layer, or stratosphere, the temperature shows no systematic variation with height, so that here there must be radiative equilibrium, little disturbed by convective mixing. The stratosphere has been explored to a height of 25 or 30 kilometres by means of *ballons-sondes* bearing meteorological instruments.

The electrical phenomena which have so far formed the subject-matter of atmospheric electricity, as ordinarily understood, relate mainly to the troposphere and the lower part of the stratosphere. Such, for instance, are thunderstorms, the surface variations of electric potential gradient, and changes in the ionic content of the air. The electrical phenomena which will be considered in this paper occur at "high" levels above the regions just named—probably above even the greatest heights yet attained by meteorological balloons.

They make themselves apparent in two principal ways. Some of them, though not all, are accompanied by luminosity; this, being observable chiefly towards the polar regions, is known as the aurora polaris. They also produce magnetic effects, which constitute our other source of information. The changes of magnetic force at the earth's surface are continuously recorded at a widely distributed network of observatories. These changes originate mainly in the upper atmosphere, directly or indirectly. The direct part is due to electric currents in the atmosphere, the indirect to secondary currents induced by the former in the conducting earth; the ratio between the two corresponding portions of the magnetic effect at the surface is 2 or 3 to 1. The earth currents flow at greater or lesser depths according to the rapidity with which the external currents vary; those associated with the regular daily magnetic variations flow chiefly at 200 or more kilometres below the surface. At times of magnetic disturbance the changes are much more rapid, and the earth currents do not penetrate so far down; telegraphic engineers know, to their cost, of the enhanced value of the currents in the surface strata at such times. The detailed relations between earth currents and the magnetic variations have not yet been fully elucidated, but the matter cannot be entered upon here, where attention will be confined to the primary phenomena occurring in the atmosphere.

Auroræ and the magnetic variations valuably supplement one another as sources of information of these electrical phenomena. Each affords certain data which are not deducible, or deducible only with difficulty, from the other. On the whole, the magnetic variations form the richer and more available fund of knowledge, since they are observable over the whole accessible portion of the earth, and, moreover, *continuously* observable—by day or night, and independently of the state of the sky. Auroræ, on the other hand, can be seen only over a comparatively limited region, and even there not by day, nor at night when the sky is cloudy or too brightly illuminated by scattered moonlight. Naturally, however, both groups of phenomena have been concurrently investigated, a proceeding assisted by the study of the changes in progress on the sun—i.e. of prominences, sunspots, and other surface features—with which auroræ and the magnetic variations are closely associated.

2. My aim in this paper has been to give a general outline of the subject, without detailed argument or references. The account is not limited to what can be regarded as certain conclusions; without, I hope, departing too far from the basis of observational evidence, conjectural views have also been admitted—a course which seems both the most interesting and appropriate method of dealing with a science of which, as of this, our knowledge is rapidly advancing. For the materials used in this synthesis the writings of many authors have been utilized: particularly, as regards the magnetic variations, the papers of Professor Schuster, Dr. Chree, Mr. Maunder, and Dr. Moos; and as regards auroræ, those of Professor Birkeland, Professor Störmer, and Dr. Vegard. While expressing indebtedness to these investigators, I do not wish to be taken as implying their agreement with all the theoretical interpretations here described, some of which are due to these and other writers, while others are independently advanced.

3. The magnetic variations with which we shall be concerned are (*a*) the regular daily variations characteristic of magnetically "quiet" days, and (*b*) the irregular, intermittent changes associated with magnetic disturbances, which when particularly intense are known as magnetic storms. On ordinary days the daily magnetic variation, approximately freed from irregular fluctuations by averaging for several days,

consists of two parts: that mentioned under (*a*) together with an additional portion introduced by, and proportional to the intensity of, the existing disturbance. The second portion, or disturbance diurnal variation, represents an inequality in the incidence of disturbance effects round the circles of latitude: the causes which produce it are those responsible for magnetic disturbance, and differ from those which originate the undisturbed or quiet daily variations. Probably no day is completely "quiet" magnetically: in the polar regions of the earth especially, magnetic disturbance is particularly intense and almost always present. Here the disturbance daily variation usually considerably exceeds the constant, quiet-day portion. But the two parts of the daily variation can be separated to some extent by comparing the daily changes on quiet and highly disturbed days, and are found to be of quite distinct types. The disturbance daily variation is approximately the same, except in intensity, when derived by comparison of specially quiet days with days of magnetic storm or with all days.

Both the disturbed and quiet day changes of magnetic force depend on locality, season, and local time. They vary also in intensity—and the disturbance changes vary in frequency—with the state of activity on the sun's surface. The solar activity, the magnetic variations, and auroræ, all manifest the cycle of change which is most familiarly known as the 11-year cycle of sunspot frequency.

The moon, as well as the sun, affects the earth's magnetic field, and there are lunar diurnal magnetic variations, depending on the moon's hour angle (or local lunar time), which are of as great interest as the ordinary solar diurnal variations, though of inferior magnitude.

4. In discussing these phenomena it is desirable to consider the earth as a whole, instead of restricting attention to the sequence of events at one or two localities on it; and to regard it as viewed from the bodies which govern its magnetic and meteorological changes; that is, from the sun mainly, but in the case of the lunar diurnal variations from the moon also.

The solar and lunar diurnal changes depend principally on the latitude of the station and the local time (neglecting, for the time being, the dependence on the sunspot epoch). These variables merely define the position of the station relatively to the sun (or, in the case of lunar time, to the moon). Locally regarded, the changes represent the effect of the moving sun, the effect being approximately reproduced at all stations round a given parallel of latitude as the sun "moves round the earth." Viewed from the sun, they appear as the passage of conditions at each station through stages characteristic of positions fixed relative to the sun as the earth's rotation carries a given station through a succession of such positions. In so far as the earth is symmetrical about its axis of rotation, these stages do not vary throughout the daily revolution, and the changes in any locality depend on latitude and local time without reference to longitude. The inclination of the magnetic to the geographic axis, however, and the unsymmetrical disposition on the earth, preclude the exact fulfilment of this condition.

From the sun, the earth is seen to be moving along in its orbit from right to left (cf. Fig. 1), and to be turning about its axis so that the front, sunlit, hemisphere is moving from left to right; provided that the observer on the sun is supposed to stand perpendicular to the plane of the earth's orbit, so as to view the North pole of the earth above the South pole. Since the sun itself is turning about its own axis in the same direction as the earth, any emission from its surface which happened to be directed towards the earth would sweep the latter, like water from a fire-hose, from right to left. Again, the moon's orbital motion round the earth is in the same direction as the earth's diurnal rotation.

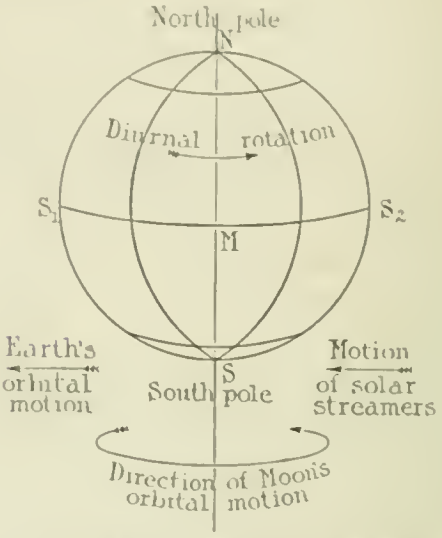


FIG. 1.—Illustrating the motions of the earth, moon, and solar streamers as viewed from the sun (§ 4).

NMS = Noon meridian.
NS_1S = Sunrise meridian.
NS_2S = Sunset meridian.

The day or sunlit hemisphere is directly visible, the night or dark hemisphere is behind; the P.M. and A.M. hemispheres are respectively to the right and left of the noon meridian.

Over the right-hand half of the earth the sun has "crossed the meridian," and the local time is after noon. This hemisphere will therefore be termed the P.M. (*post meridiem*), and the left-hand the A.M. (*ante meridiem*) hemisphere. Similarly we may speak of the sunlit and dark, or day and night hemispheres, which are separated by the "twilight circle" of the earth. This circle is composed of the sunset and sunrise meridians (on the right and left respectively), which with the noon and midnight meridians (in the plane containing the sun) divide the earth into four equal quadrants.

5. Before describing to what causes the quiet-day and disturbance magnetic variations are due, it is well to exclude explicitly certain possibilities which, though they naturally suggest themselves, are not confirmed on examination. The magnetic variations are not caused by direct magnetic action on the part of the sun or moon, nor do they represent the varying magnetic field of streams of electric charges of one kind, moving separately from charges of the opposite

kind, whether within or outside the atmosphere. They are, in fact, variations in the magnetic field of electric currents of the ordinary type flowing in more or less horizontal layers in the upper atmosphere; that is, currents in which the magnetic field is unaccompanied by any appreciable electrostatic field. They are produced, moreover, in essentially the same way as are the currents generated in ordinary commercial power stations, i.e. by electromagnetic induction. In the present instance the earth's permanent magnetic field (the origin of which is still unknown) constitutes the magnetic field of the terrestrial dynamo. The atmosphere, itself in motion owing to various causes, is the armature; while certain layers which are specially ionized (mainly by solar action) are the conductors in which the flow of electric current takes place.

The atmospheric motions concerned are of two kinds, one set being associated with the quiet-day magnetic variations, while the other set is connected with magnetic disturbance. The latter motions originate in and are confined to a region high up in the stratosphere: the former extend throughout the troposphere and a large part of the stratosphere, but are electromagnetically effective only at a considerable height above the base of the stratosphere. Below this level the air is not sufficiently conducting to allow any appreciable flow of current, so that the irregular convective motions in the troposphere (§ 1) have no part in producing the magnetic variations.

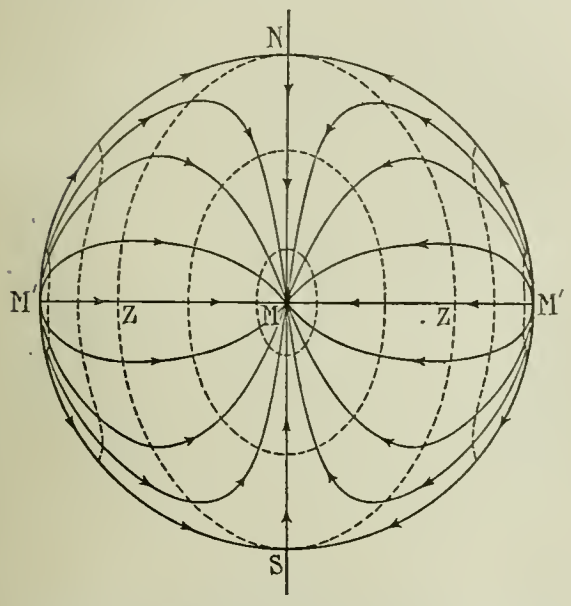


Fig. 2.—Lines of equal pressure (dotted) and of instantaneous direction of motion in a tidal system of circulation in the earth's atmosphere, viewed from the tide-producing body (§ 6).

In this drawing there is supposed to be no lag of phase, so that maximum pressure occurs at M and minimum at M′. The opposite side of the earth resembles that shown here. The meridians NZS are lines of zero pressure, separating regions over which the pressure is in excess and defect respectively.

6. The set of atmospheric movements which gives rise to the quiet-day diurnal magnetic variations consists of two great world-wide circulations of tidal type. One is a true tidal motion, due to the moon. The other, of similar character but of different phase and fifteen-fold the amplitude, is of solar origin; it is mainly produced by thermal—not tidal—action. The difference in phase indicates a difference of orientation of the two systems of circulation relative to their governing bodies the sun and moon. Moreover, the orbital motion of the moon causes the lunar tidal system of circulation to shift relative to the solar system, completing one revolution, in the same sense as the earth's diurnal rotation, in a lunar month.

In each case the movement of the air is mainly horizontal. The current-lines in the case of such tidal motions are indicated in Fig. 2, where for simplicity a particular phase, different from that of either the solar or lunar circulations, has been adopted. The maximum velocity occurs at the equator, and in the solar case is approximately 1 kilometre per hour. The velocity is nearly the same at all levels up to a considerable height; the solar diurnal circulation, however, seems not to extend so far up as the lunar circulation: the latter is present in the auroral layer, at a height of 100 kilometres, while the solar diurnal movement does not seem to exist there.

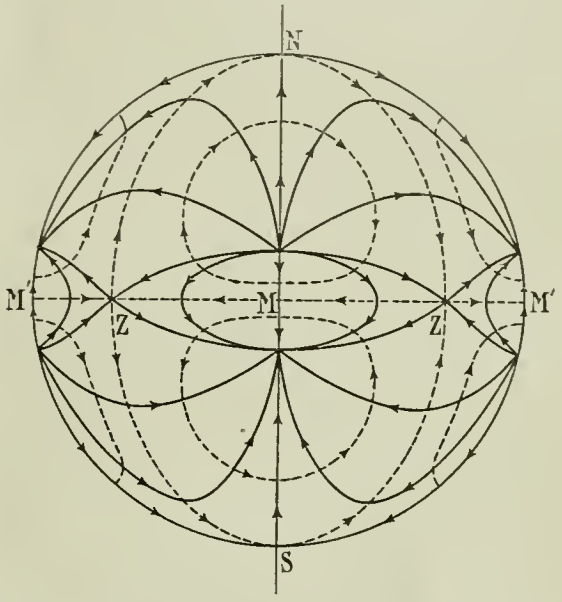


Fig. 3.—Electric current-lines (dotted) and lines of horizontal magnetic force at the earth's surface, resulting by electromagnetic induction from the tidal atmospheric circulation of Fig. 2 (§ 6).

The layer in which the electric currents flow is for simplicity assumed to be of uniform conductivity. The obliquity of the magnetic to the geographical axis of the earth is neglected. The above curves give an approximate representation of the semi-diurnal component of the diurnal magnetic variations (except as regards phase), viewed from the sun or moon.

Like all tidal circulations, these two movements are of semi-diurnal type; that is, the motion in either case is the same over the two halves of the earth separated by any meridian plane. The motion being horizontal, the induction takes place across the vertical component of the earth's magnetic force. This component, it should be recalled, is downwards in the Northern, and upwards in the Southern hemisphere, but is otherwise nearly symmetrical with respect to the equator. The

induced electromotive force is perpendicular to the direction of horizontal motion, to the left in the Northern, and to the right in the Southern hemisphere.

The systems of electromotive force, like those of atmospheric motion, are semidiurnal (cf. Fig. 3); but the systems of horizontal electric currents impelled by these forces in the layer which is sufficiently conducting to give scope to them, are not of this type. They are not identical over the two halves of the earth separated by any arbitrarily chosen meridian plane: their intensity is, in fact, much greater over the sunlit than over the dark hemisphere. This is shown by the considerably enhanced activity of the solar and lunar diurnal magnetic variations resulting from these currents, during the hours of solar daylight, and during the season of the year (summer) when, at a given station, the rays of the sun are most directly received. The lunar diurnal magnetic variations exhibit the effect particularly clearly; since the lunar tidal system of circulation progressively advances relative to the sunlit hemisphere (*vide supra*), the lunar hours during which the electromagnetic effect is magnified regress throughout the lunar month; the character of the lunar diurnal magnetic variations consequently changes regularly in the course of a lunation, the activity being greatest during the hours of solar daylight at each epoch.

Besides this daily and seasonal variation in the intensity of the quiet-day magnetic changes, the latter vary considerably in intensity (while preserving their type almost unaltered) throughout the cycle of solar activity. The one variation indicates a dependence on the position of a station relative to the sun, the other on some intrinsic solar factor affecting the earth as a whole. Both effects are explained by supposing the electric *conductivity* of the layer of air in which the currents flow to vary in the manner described; and that this is because the conductivity is produced by some solar ionizing agent. This agent, as I have shown elsewhere (in a paper communicated to the Cambridge Philosophical Society) is ultra-violet radiation, which must be emitted more strongly at sunspot maximum than at sunspot minimum. It is shielded from the dark hemisphere, but over the sunlit hemisphere it penetrates to a considerable depth in the earth's atmosphere, much below the under limit of the auroral layer (about 100 kilometres above the ground). It seems likely that it is the lower surface of the layer thus ionized by solar radiation which is responsible for bending "wireless" waves round the earth, and so increasing the distance over which messages can be transmitted in this way. Professor G. N. Watson has recently given conclusive proof that, unless prevented by the presence of such a conducting layer, the electric waves would in large part travel outwards into space, instead of, as they are observed to do, round the globe.

The ionization produced by the ultra-violet radiation (which is all absorbed in the atmosphere at a great height above the ground) is most intense over regions which receive the sun's rays vertically, and it diminishes to a low value near the twilight circle and over the dark hemisphere. If the ionization is associated with the production of luminosity, we are prevented from observing the latter owing to the presence of daylight, so that the quiet-day magnetic variations are unaccompanied by any visible atmospheric phenomena. The auroræ are *not* associated with these electromagnetic effects, of whose existence the quiet-day diurnal magnetic variations afford the sole indication.

7. The magnetic variations to which auroræ are related are the magnetic *disturbance* changes, including, of course, the disturbance diurnal variation. As regards the sun, moreover, auroræ are connected with *locally* agitated regions on its surface, instead of to the surface as a whole (whence, it seems probable, there proceeds the æthereal radiation which ionizes the lower conducting layer in the earth's atmosphere, as just described).

Magnetic disturbances and auroræ are produced by the injection into the earth's atmosphere of electric corpuscles projected in confined streams from disturbed regions on the sun. These streams may be emitted in any direction, so far as we know at present; their existence is made known to terrestrial observers only when a stream is projected so that, in the course of the solar rotation, it sweeps over the earth. The streams are often of considerable angular diameter, e.g. 10 degrees or more. As the angular diameter of the earth, viewed from the sun, is only 18·6 seconds of arc, it becomes completely enveloped in the streams; and often remains so for hours or even days, notwithstanding that the relative speed of the streams at the distance of the earth enables them to sweep right across the earth in 35 seconds. The latter fact explains why magnetic storms, the particularly intense and world-wide disturbances which occur when the earth is enveloped in a dense solar stream, are observed to commence at almost the same instant all over the earth. Again, since disturbed regions on the sun often continue to emit streams of electric corpuscles in the same relative direction for a period of more than one solar rotation, a given stream may traverse the earth more than once. This accounts for the observed tendency for magnetic conditions to recur after an interval equal to the time taken by a stream to reach the earth again, after a complete rotation with the sun. This, which is shown by quiet, no less than by disturbed conditions (corresponding respectively to the absence and presence of streams in the earth's neighbourhood) is only a tendency and not a definite periodicity: for the sequence of streams existing at any given time is continually being interrupted by the cessation, or alteration of direction, of old streams, and the initiation of new ones.

8. The streams seem to consist entirely or predominantly of corpuscles having the same sign of electric charge. They are ejected from the sun with a speed comparable with that of light, and travel outwards approximately in straight lines. When they approach the earth, however, their rectilinear motion becomes modified owing to their entry into the earth's magnetic field. A magnetic field, of course, exerts a force on a moving electric charge, perpendicular to the plane containing the direction of the magnetic force at the point instantaneously occupied by the charge, and to the line of motion of the charge. In a uniform magnetic field an electric charge will, in general, describe a spiral path, the axis

of the helix lying along the direction of the magnetic force. In the earth's field, which is uniform neither in direction nor in intensity, the motion of the solar corpuscles is more complicated, and the problem of calculating their paths has not yet been completely worked out. Some important results have, however, been arrived at. It appears that, though in an intense stream the particles seem to impinge upon the atmosphere from all sides, there is a strong tendency for them to be drawn in towards the earth's magnetic poles; yet not so as to fall most numerously at the magnetic poles themselves, but rather around two zones, one centred at each such pole. The radius of the zones can be calculated approximately, but depends upon the nature and speed of the particles. The zones are naturally identified with the zones of maximum auroral frequency; these are centred as described, and have a radius of about 20 degrees. This is much greater than the radius calculated on the assumption that the solar corpuscles are β-particles (i.e. negative electrons, having a mass much less than that of a hydrogen atom, though travelling with great speed). On the other hand, the observed agrees pretty closely with the calculated radius, if the particles are supposed to be α-particles, positively charged, but otherwise identical with ordinary atoms of helium moving with great velocity.

9. Three principal consequences follow from the injection of the solar corpuscles into the earth's atmosphere. First, the particles break up many of the molecules which they encounter before being brought to relative rest in the atmosphere. This means that the layer in which the retardation takes place is ionized; during times of magnetic disturbance, therefore, there are two conducting layers instead of only one. Secondly, where the ionization is particularly intense it is accompanied by luminosity, observed as auroræ; this accounts for the polar distribution of auroræ, and their association with magnetic disturbance. The production of the latter depends on the third effect mentioned, viz. the electrification of the air. This is accompanied by electrostatic forces of sufficient intensity to impart an important degree of motion to the extremely rarefied air. This is the second of the two types of motion referred to in § 3.

The general nature of the movement can be readily inferred. The mutual repulsion of the entangled charge spread over the world-wide spherical layer produces an upward, outward movement, as in a charged soap-bubble. Thus the air travels vertically upwards—except during the first few minutes of a magnetic storm. For at first the downward momentum of the injected particles depresses the air, before the electricity has accumulated sufficiently to reverse the motion.

In the process of electromagnetic induction the vertical movement acts by cutting across the horizontal component of the earth's magnetic force. Since the latter is directed from North to South, the upward motion induces an electromotive force from East to West, while the initial downward velocity induces one in the opposite sense. An electric current flowing from West to East, as in the latter case, will increase the horizontal magnetic force at the earth's surface; this is what is usually observed in middle and lower latitudes during the first few minutes of a magnetic storm. Afterwards the reversal of motion of the air, and of the resulting electromotive force, causes a diminution in the horizontal magnetic force; this is one of the most characteristic features of magnetic storms.

10. The electromagnetic effects of a storm are not quite of the simple type which might be expected from the remarks of § 9. The complication arises mainly from the unequal distribution of the corpuscular injection. This inequality is not altogether due to the deflection of the particles by the earth's magnetic field; in part it is due to the circumstances of emission from the sun. Over any given region near the auroral zone, for instance, visual observation of the auroræ strongly suggests that the injection is both "patchy" and intermittent.

This causes the ionization of the air to vary considerably from place to place, and the inequalities of conductivity thus set up are likely to endure for some hours. Consequently, even if the electromotive force were quite uniform in direction and intensity, the current-flow would be far from uniform. As the inequalities of conductivity are probably greatest in the polar regions, we have an explanation of why the magnetic disturbances in those parts are specially irregular. The great *intensity* of disturbance there is due to the high average value of corpuscular injection and ionization around the poles. I have found evidence, which will be discussed in a future paper, that the conductivity in the "maximum auroral zone" is particularly intense.

Besides these comparatively small-scale inequalities of precipitation and conductivity, the study of the disturbance portion of the diurnal magnetic variations (which represents the inequality of disturbance round the circles of latitude) shows that the solar corpuscles fall more intensely over the P.M. than over the A.M. hemisphere. Thus the two solar ionizing agents have different "most favoured hemispheres"—the sunlit one being that most affected by the other agent, the ultra-violet wave radiation.

This longitudinal inequality of conductivity in the auroral layer (here regarded as extending all round the globe, whether or not luminous effects are visible) shows itself in the production of a greater diminution of the horizontal magnetic force, in middle and equatorial latitudes, over the P.M. than over the A.M. half of the earth. This appears clearly from the disturbance diurnal variation of horizontal magnetic force in the latitudes mentioned (cf. Fig. 4); it would necessitate too long a digression to explain how the disturbance diurnal variation in the other magnetic "elements" and in other latitudes likewise indicates the existence of excesive precipitation of corpuscles over the P.M. hemisphere and round the "auroral maximum" zone.

11. One interesting circumstance connected with the non-uniform injection of charge is that, while it results in the existence of inequalities of electrical conductivity over the spherical layer affected, the charge itself is continuously re-distributed so as to

keep the surface density of electrification practically uniform. This is true, of course, of any spherical electrified shell of sufficient (though not necessarily uniform) conductivity. In the case before us the conductivity seems quite large enough to permit the re-distribution to take place with a rapidity altogether exceeding that of the escape of the charge right away from the atmosphere—an escape which does, however, ultimately result in the course of a few hours or days, according to the duration of precipitation) from the upward motion referred to in § 9. The re-distribution seems to be of an oscillatory character, and so to be accompanied by the propagation into space of Hertzian waves of wave-length approximately equal to the

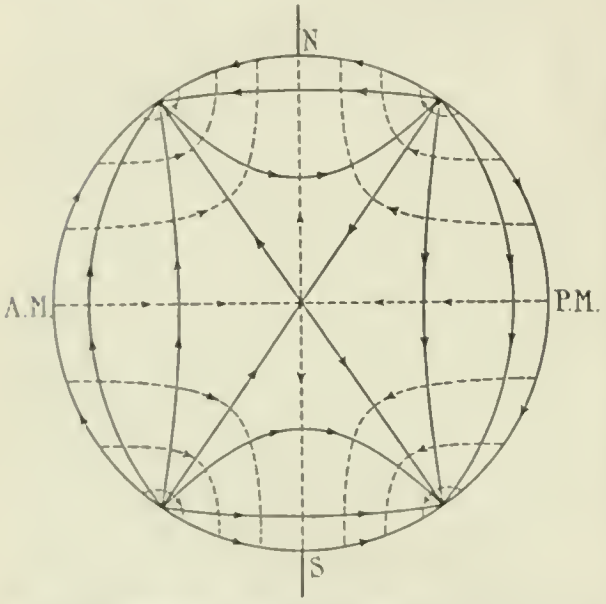


FIG. 4.—Current lines (dotted) and lines of horizontal magnetic force at the earth's surface, corresponding to the disturbance portion of the solar diurnal magnetic variation (§ 10), as viewed from the sun. The complications near to the pole, resulting from the specially high electrical conductivity of the upper atmosphere in the auroral zone, are neglected in this diagram.

diameter of the earth. The period of these waves is about one-twentieth of a second.

The surface density of charge thus being maintained uniform over the earth, the upward electrostatic force tending to produce the vertical motion of the air is likewise uniform. The vertical motion itself, however, will not be uniform, since it will be unequally resisted by the mechanical force acting downwards on the induced currents, tending to prevent their production. This mechanical force is proportional to the intensity of the horizontal currents and of the horizontal component of the earth's magnetic force. The latter is least at the poles and greatest at the equator, while the former is probably greatest in the auroral zone. It is therefore not very easy to estimate the distribution of the vertical motion over the layer.

One further circumstance in this connection deserves mention: the precipitation of electric charge into the atmosphere does not produce an "electric storm" at the earth's surface, as well as a magnetic storm (or minor magnetic disturbance). During a world-wide magnetic storm, indeed, in which the extension of the corpuscularly ionized layer all round the earth permits a uniform re-distribution of the charge, no change in the electrostatic field at the earth's surface would be expected—for a charge on the outside of a conductor does not produce any electric force in its interior. But even in the case of a minor disturbance, due to a stream of corpuscles which falls upon, and renders conducting, only a limited portion of the upper atmosphere, no electrostatic change at the earth's surface is observable. This seems to be owing to the electric shielding effected by the other ionized layer, which extends all round the earth (though it is most conducting over the sunlit hemisphere). This layer is lower than the other, so that local charges in the auroral layer do not electrically affect the interior of the "diurnal variations" layer (§ 5).

The grounds for the conclusion that the latter is lower than the auroral layer may be briefly described here.* If the solar semi-diurnal atmospheric circulation, which is produced by thermal action at or near the earth's surface, extended up into the auroral layer, the conductivity existing there at times of magnetic disturbance would permit an increased induction of "diurnal variation currents" at such times. In particular, the semi-diurnal component of the solar diurnal magnetic changes should be increased; this is not found to occur, the modification in these changes due to disturbed conditions being of quite different type (cf. Figs. 3 and 4). The lunar atmospheric tide, on the contrary, is produced by forces acting on each portion of the air throughout its whole extent, so that it should extend higher up than the solar diurnal circulation, and this is confirmed by the fact that the lunar semi-diurnal magnetic variation is increased at times of disturbance. Hence the layer in which the quiet-day magnetic changes are produced must be lower than the auroral layer. Assuming that the latter is situated at approximately the same height in all latitudes (i.e. that the penetrating power of the corpuscles is independent of the latitude to which they are deflected), the former layer may be ascribed to a lower level than 100 kilometres.

12. Before proceeding to consider the physical nature of the solar corpuscles, and their connection with the ultra-violet light which ionizes the lower conducting layer of the atmosphere, some of the principal features of auroræ must be touched on.

The existence of a zone of maximum auroral frequency round each pole of the earth's magnetic axis, and of radius about twenty degrees, has already been mentioned. Near these zones auroræ are visible on almost every night on which the conditions of seeing are suitable. When specially intense streams of corpuscles are in the earth's neighbourhood, however, precipitation of intensity sufficient to produce luminosity occurs over a more extended region. At such

* They are given more fully in a paper communicated to the Cambridge Philosophical Society, December 1918.

times, which are marked by the occurrence of unusually violent magnetic disturbance, i.e. by magnetic storms, auroræ are observed over a large range of latitude, simultaneously in each hemisphere. Occasions on which auroræ are thus visible so far south as London, for instance, occur on an average about six times a year.

There are many different forms of auroræ—in particular, arcs, streamers, curtains and coronæ. But it seems not unlikely that all, or nearly all, these are merely different aspects of aggregations of one elemental unit, the simple streamer or ray. When curtain auroræ are viewed from a point directly beneath them they are seen to consist of a thin wavy and discontinuous series of parallel streamers. The auroral corona appears to be formed of a rather different arrangement of similar rays. This unity of composition agrees with the evidence of height determinations (which show that all types of auroræ come down to approximately the same level) in indicating that there is no essential physical difference between the various forms. The lower limit of height is 100 kilometres above the ground, very nearly, in all cases. Vegard states that no auroræ has been certainly proved to extend downwards below a height of 95 kilometres. The great majority lie between 100 and 130 kilometres, and within this range there are two well-marked levels of maximum frequency of occurrence, corresponding to lower limits of 100 and 106 kilometres. This indicates that the solar corpuscles probably fall into two homogeneous groups, travelling with rather different speeds and therefore having different powers of penetration. The heights named do not seem to vary with latitude, or from year to year; thus the degree of activity on the solar surface does not affect the nature and speed, but only the intensity and frequency, of corpuscular emission from the sun.

13. There is a tendency for the brightest part of auroral bands and rays to occur at their lower edge, though in the case of rays it is occasionally found some distance above this level. The fact has a bearing on the question as to the precise nature of the solar particles, tending to confirm Vegard's hypothesis that they are α-particles, as the radius of the maximum auroral zone suggests (§ 8). Such particles, of molecular mass, are found to penetrate to a definite distance when projected into a gas; they travel in practically straight lines for this distance and then come to a relatively dead stop when their velocity is reduced to that of the surrounding molecules. The ionization (and luminosity, if such is produced) is greatest shortly before they reach their limit of penetration. These features, as we have seen, are manifested by auroræ, and are quite distinct from those which characterize the projection of negative electrons, β-particles, into a gas. Moreover, a stream of α-particles has much greater power than has a stream of β-particles of being projected intact in free space to a great distance; for the charge on an α-particle is only twice that of a β-particle, while the momentum of the α-particle is far greater than that of the other. It is thus better able to resist the dispersing influence of the electrostatic repulsion mutually exerted by the members of a stream of particles all of one sign of charge. A further argument tending to the same conclusion rests upon the explanation which has been given of the increase in the earth's horizontal magnetic force during the first few minutes of a magnetic storm. This (§ 9) was attributed to the downward momentum of the injected particles, and the fact that the momentum is able to manifest itself in this way is much less surprising if the particles are as heavy as helium atoms than if they are mere negative electrons.

14. Two further points which arise for consideration relate to the circumstances of the corpuscular emission from the sun, and to the connection between the ultra-violet wave-radiation and the corpuscles. These, if α-particles, may possibly be products of radio-active processes occurring on the sun. This would explain, in a way not easy on any other hypothesis, the high speed and homogeneity of the corpuscular rays (§ 12). Again, the suggestion derives support from the existence of the other solar ionizing agent, the ultra-violet light radiation, which, as we have seen, is more penetrating than the corpuscular emission. In the past, before the evidence for the effective presence of *both* kinds of radiation was recognized, discussion concerned itself with the relative merits of the two—corpuscles and ultra-violet light—regarded as *alternative* ionizing agents. Two of the difficulties were as follows: in the case of the corpuscles, the accumulation of charge in the earth's atmosphere was mentioned as an argument against them—in the present review, the escape of accumulated charge is put forward as a main factor in the production of the magnetic storms associated with solar disturbance; in the case of the alternative agent, it seemed hard to understand how the ultra-violet light, supposed absorbed in the earth's atmosphere (since it does not reach the ground-level), could escape from the *sun's* atmosphere. Moreover, regarding the ultra-violet light as simply part of the ordinary radiation of the sun, treated as an incandescent "perfect" or "black-body" radiator, Swann had shown that the amount, even if the whole escaped from the sun, was quite inadequate to produce the observed ionization of the upper atmosphere. Both these difficulties are avoided if we suppose the ultra-violet light to consist of γ-rays, i.e. the extremely penetrating wave-radiation which in certain radio-active processes accompanies the emission of α-particles and β-particles. These γ-rays are immensely more penetrating than either β- or α-particles, so that as the latter prove able to escape from the sun's atmosphere, it is natural that the γ-rays should likewise do so; how far the speed of the particles is reduced in the solar atmosphere we cannot say, but the γ-rays which escape will maintain their superior penetrating power, and so ionize a layer in the terrestrial atmosphere lower than the auroral layer. The rays do not travel to a definite distance before absorption, as do the α-particles; their intensity diminishes exponentially with the mass of the gas traversed. As the density of the earth's atmosphere increases approximately exponentially with depth (reckoned from the outside), it is probable that the lower ionized layer in the atmosphere is ill-defined both above and below; the higher-lying auroral layer, on the contrary, though ill-defined above, has a sharply-marked lower limit.

The fact that both ionizing agents, though of such distinct kinds, are more intense during years of great than during years of little solar activity argues for the existence of some physical connection between them, and is thus accordant with the hypothesis of their radio-active origin. The γ-radiation however, seems to vary continuously and gradually, while the streams of corpuscles are discontinuous and intermittent. I am inclined to attribute this to the fact that the radiation, whether produced locally or as seems more likely, all over the sun's surface, will spread out in all directions—what we receive at the earth coming from the whole of the emitting area. In the case of the corpuscles, probably they either cannot escape at all from the sun's general magnetic field or can do so only in diffuse masses except where the intense magnetic fields which Professor Hale has shown to exist over sunspots provide a "guide," analogous to a channel, along which they can stream outwards. The undoubted connection between disturbed areas on the sun and magnetic storms tends to support some such conclusion. Perhaps the study of the magnetic fields of sunspots will in time enable us to refer a given magnetic storm to a particular disturbed region on the sun by indicating which region is associated with lines of magnetic force directed towards the earth. Attempts by other methods to establish such a connection have never yet met with success. Hitherto there has been great uncertainty as to the time taken by the solar corpuscles to reach the earth; if they are α-particles the time of passage can be assigned within fairly narrow limits, as from about two to three hours.

Nothing has so far been said about the β-particles emitted during the radio-active processes mentioned. It may be that these negative particles escape from the sun diffusely, or it in streams with the α-particles, that they become dispersed owing to their much greater deviability, before they reach the earth. Certainly they must escape from the sun in some way, as it is not to be supposed that the sun is steadily accumulating a negative charge, while there seems to be no evidence that two kinds of corpuscles reach the earth.

If the above suggestion is confirmed, that radio-active transformations on the sun are responsible for the emissions which affect the earth's atmosphere, such processes must play a much greater part in the economy of the sun than has generally been supposed, and they must be intimately connected with the cycle of variation of solar activity, for the ultra-violet wave radiation (here identified with γ-rays) is twice as intense at some sunspot maxima as at sunspot minima.

15. I can complete the present account of the high-level atmospheric electrical phenomena which it has been our task to pass rapidly under review. The subject is by no means "cut and dried," and I have failed if any other impression of it has been given than that of a kind of investigation which is interveaved on many hands, each of which finds the unknown territory more extensive than can be glimpsed. So far as concerns the restricted aspect of it which has been considered here, the subject may seem to be a branch of meteorology, that science which deals with the upper atmosphere just exactly within the reach of our instruments. As yet it is too early to say how far a knowledge of these phenomena of the upper stratosphere is likely to assist in solving the important practical problem of weather prediction. These phenomena are, however, even more closely connected with solar physics—certainly, at any rate, in a more varied way—than is general meteorology, or than the latter is with the subject of this paper: and the study of them seems likely to contribute reciprocally to the advancement of solar physics in a way of which ordinary meteorology shows no promise. The secondary currents induced within the earth by those flowing in the upper atmosphere again extend the subject into a region quite distinct from atmospheric dynamics and thermodynamics, and provide one of the few means of research into the properties of the deep-lying interior of the earth.

While these studies may be expected to further other branches of science, those by the aid of which they must themselves be advanced are very numerous. Among them general physics—particularly electro-magnetism, radio-activity, and spectroscopy—and mathematics, in addition to the sciences already named, come foremost. On the observational side the opportunities for valuable research are likewise numerous and varied, and, as in the case of astronomy, though to a less extent, many of them have been ably utilized by amateurs, as well as by those who have worked under the auspices of institutions maintained for the purpose of research. Probably few electrical engineers have leisure to devote themselves personally to the study of these somewhat remote ramifications of the science of electro-magnetism, but I hope that it may not be without interest to them to consider briefly such examples of how the principles underlying the more familiar applications of electricity are illustrated, in various ways and on a large scale, in Nature.

Note (*Added* 15 *July*, 1920): During the 15 months which have elapsed since the above paper was written, further study has led to the recognition of new facts and considerations which necessitate revision of some of my statements, in important though not fundamental respects. Professor Lindemann has published a criticism of part of my theory of magnetic storms, and proposed an alternative version. For reasons which cannot be entered upon in this Note, I am unable to accept this version, and I adhere to the view that storms are produced by streams composed mainly though not entirely of one sign of charge. The lunar diurnal magnetic variation proves to be more complicated than I had anticipated, and tends to suggest that there are *three* and not only two ionized atmospheric layers associated with the magnetic variations. Again, the escape of the charge during a magnetic storm would seem to involve less motion of the air than I had hitherto supposed, since the ions have a considerable free range in the rarefied air. A consideration of the different degrees of mobility of the positive and negative ions leads me to conclude definitely that the corpuscles responsible for a magnetic storm are negatively charged, so that the suggestion that they are α-particles must be withdrawn.

Discussion before The Institution, 22 May, 1919.

Sir F. W. Dyson: When one considers the great variety of phenomena which are dealt with, namely, auroræ, sunspots, solar rotation, tides in the atmosphere, magnetic variations, and the different kinds of variations on the ordinary quiet day, and those which occur at times of magnetic storms, it is obviously very difficult to embody all these diverse phenomena into one theory as the author has done. There are a number of observatories throughout the world at which great masses of records are accumulated, and to a great extent nobody knows what to do with them. It is very easy to accumulate these observations, but it is a very difficult matter to co-ordinate them and make a consistent theory connecting them all. That is what the author has done. I take it that as far as magnetic observations go, one of the main points on which he bases his theory is the difference between the daily movement on ordinary quiet days and that remarkable movement which is not dependent on the local time of the observatories, the remarkable movement in the horizontal forces which occur during magnetic storms. That apparently is one most regular feature among the very irregular changes which occur in magnetic storms.

Dr. W. H. Eccles: The subject is of very general electrical interest, but I feel that I am concerned with only one possible application of it, namely, wireless telegraphy. All wireless men will be very grateful to the author for introducing into this subject the novelty of definiteness. The author lays down some very definite figures. He tells us, for instance, that there is a layer in the atmosphere at a height of 100 kilometres down to which the auroræ descend, that is to say down to which the alpha particles can descend, and that beneath this there are permanent ionized layers forming a definite ceiling just such as we have wanted to know of in wireless telegraphy for very many years. The second thing we wanted in wireless telegraphy was something in the nature of a conducting layer produced by sunlight daily under that ceiling. The reasons for our demands are well known. In the night one can transmit to distances far beyond what could be attained by unassisted diffraction, almost as if the divergence were in two dimensions only. In the day the ranges drop enormously, apparently because the sun ionizes lower levels and brings in rather heavy absorption of electric waves, or too rapid bending of them down towards the earth, so that they are lost. For instance, in the Dutch East Indies certain experiments by de Groot between a fixed station and a warship over very hilly country showed that signals were better in the daytime for about 200 kilometres than they were at night. At night the hills deflected the rays from the fixed station towards high layers whence they were reflected down beyond the distance to which the ship was sent. But in the daytime the rays were apparently bent downwards before they reached that upper layer, and therefore the ship close up received the signals. The third thing to be investigated from the wireless aspect is the lower atmosphere, where moisture and air currents and that kind of phenomena enter, which we know have some influence on signalling. That again is provided by the author's paper. I might mention that the effect on signals of the troposphere has been proved by some observations not yet published between Swan Island off the coast of South America, and New Orleans. The wireless men, I think, scarcely wanted any corroboration that the three layers had those three functions, but lately Professor G. N. Watson has obtained a mathematical solution of the problem of the propagation of waves partly by diffraction and partly by reflection from, or perhaps absorption in, a conducting atmosphere, and he has found that he can corroborate by his analysis a famous formula that has been in use for many years by wireless telegraphists for estimating the ranges for long distances. That formula depends, I understand from the present paper, on the absorption and bending in the middle atmosphere; it does not refer to reflection from what I have called the ceiling, the bottom of the permanently ionized atmosphere. I should like to have the author's opinion on that point. I realize very keenly the enormous labour required to reduce all the curves and observations he has discussed, and I am very grateful that he has put his results into simple language and given us a clear mental picture of the phenomena.

Dr. G. N. Watson: I have very little to say beyond what Dr. Eccles has just said, except to ask one or two questions about numerical results. I have investigated the problem of the layer in the upper atmosphere from the mathematical point of view, and I find that if we suppose there is a ceiling with a fairly definite boundary, as the form of the aurora seems to suggest, then it is possible to obtain Austin's famous numerical formula in wireless telegraphy, that the magnetic force produced by wireless disturbance varies as the exponential of a negative multiple of the distance from the transmitter. The precise multiple in Austin's formula is given as 9·6 divided by the square root of the wave-length (measured in kilometres), and that number is exactly produced if the proper height and conductivity are given of the layer. The formula I have obtained agrees with Austin's if $\sigma h^2 = 1{\cdot}67 \times 10^{11}$, where h is the height of the layer in kilometres, and σ is its conductivity, measured in rational units; so that if one takes the auroral layer at the height of 100 kilometres, that gives a conductivity to the layer which is not very widely removed from the conductivity of fresh water. I should very much like to know whether the author is able to give any information that that conductivity can be obtained from the electromagnetic phenomena which he has discussed this evening. The formula that I obtained is not inconsistent with what Dr. Eccles has just mentioned on the subject of the increased difficulty in signalling by daylight as opposed to signalling by night. If the conductivity is diminished, it is more difficult to signal, so that it is quite conceivable that the increased difficulty in signalling by daylight may be due partly to the lowering of the layer on account of the sunlight, and partly to a change in the conductivity of the lowest level of the ionized layers. Another

point which I should like to ask the author about is this: does he think the sudden sharp boundary of the auroral layer is produced by the fact that the conductivity suddenly drops practically to zero or drops below a certain amount beyond which the outer particles cannot get through?

Mr. E. A Reeves: I am interested in terrestrial magnetism especially as regards the geographical distribution of magnetic phenomena, but one cannot deal with that subject without having something to do with atmospheric electricity. This geographical distribution has led me at times to consider the distribution of the aurora, both in the northern and in the southern polar regions. It is usual to suppose that the lines of relative frequency of the aurora follow more or less regular curves round the magnetic poles, and I think that this is stated to be the case in the paper. However I am not sure that these curves are not, to some extent, influenced by the areas of maximum magnetic intensity in high latitudes. In the North Polar regions the curve of maximum frequency includes quite a large part of Arctic America, and then is pulled out somewhat in the form of an ellipse towards North-East Asia and the Bering Straits in the general direction of the Asiatic area of great intensity, leaving the magnetic pole nowhere near the centre. An inspection of any recent chart of the aurora-frequency curves will show this to be the case. The paper is very interesting, but we require more facts and better means of observation for detecting the direction of the particles or corpuscles that are ejected from the sun. I rather hoped that something would be said, not merely about disturbances in the diurnal changes or the more abnormal disturbances of magnetic storms—but about the slow and more or less gradual and regular annual change in declination or inclination.

Mr. E. W. Maunder: My own connection with magnetic storms has been from a different side from the author's, for my field of observation has been mainly concerned with sunspots. Soon after I came to Greenwich Observatory, some 46 years ago, Mr. Ellis was appointed Superintendent of the Magnetic Department there, and I learned from him the chief characteristics of magnetic storms, and to take an interest in them. In the year 1882 several very large spots were seen on the sun, two of the largest occurring in April, and a third, larger still, in November of that year. I was much struck by the fact that we had violent disturbances of the magnets, two of them in April, while the first two spot-groups were on the sun, and the third, and greatest, in November, contemporaneously with the chief sunspot of the year. From that time forth I felt sure that there was a direct connection between solar activity and magnetic disturbances, and the impression was greatly confirmed in 1892 when another great spot of enormous dimensions crossed the disc, and, as it passed the central meridian, there was another great magnetic disturbance. I tried then to see if I could make out any connection between these two orders of phenomena, and I made a catalogue of the largest spots that I had had under my notice, and also one of the principal magnetic disturbances, of which Mr Ellis supplied me with a list, but I could not make anything out of the comparison except that there was a sort of general relation between the two phenomena. On the whole it might be said that in a year when there were many big spots, there would be a large number of disturbances; but there might be occasions when the sun would not have a single spot upon it and yet there would be a distinct magnetic disturbance, while on the other hand we might have a great spot on the sun and no answer to it in magnetic phenomena. Later on, when the next sunspot cycle was beginning to become active, in 1903, the question came up again. On the 12th October, 1903, we had a very fine group of spots, and quite a distinct magnetic storm. Then on the 31st October of that year there was a tremendous magnetic disturbance, one of the biggest and most world-wide that I can remember, but the principal spot on the sun that day was only of the second- or third-rate order. It seemed to call for a fuller explanation as to how it was that with a very large spot we got what I might call a second-rate disturbance, while with a smaller spot a first-class storm was observed. I tried to make out a list of all the magnetic storms and all the sunspots, and see if I could work out any sort of satisfactory correlation, and in the course of the inquiry it struck me that it would make my task much easier if I took the magnetic storms first—as they were less numerous than the spot-groups—and computed the longitude of the centre of the sun's disc for every time that a magnetic disturbance commenced. While I was engaged in forming that catalogue, I came across the explanation of my difficulty. In the autumn of 1886 four successive magnetic disturbances occurred when the same longitude of the sun was on its central meridian, and in the autumn of the following year there was again a succession of four magnetic disturbances when the same longitude of the sun was on the same meridian—not the same longitude as the first set, but about 13° distant from it. I saw at once that there was only one hypothesis upon which these occurrences could be explained, namely, that the sun had had a direct effect upon the earth, and that its influence had been conveyed from thence to this world in definite, restricted streams. Inasmuch as most of the magnetic disturbances began sharply—many of them at the same instant of time all the world over—they could not be due to a general influence from the whole surface of the sun; the influence must come from a limited region, and could only be transmitted to the earth along restricted streamlines, not by general radiation in all directions through space. After that I went through the whole record of magnetic disturbances preserved at Greenwich from the very beginning of the method of photographic registration of the movements of the magnets, and when the longitude of the central meridian of the sun was computed for each time of disturbance, it became evident that there was a strong tendency for magnetic disturbances to recur when the same longitude of the sun came round a second time. As an illustration, I may mention that the great spot of February 1892, which had an area of 3,500 million square miles, had diminished to one-fifth its former area when it came round again in March, yet directly it reached the same part of the sun's apparent

disc, where it had been at the time of the first disturbance, another disturbance almost as great occurred. It was clear, therefore, that although the sunspot had nearly died out, yet the magnetic effect transmitted from the sun was practically undiminished. This cleared up the difficulty that I had felt of explaining how it was that we might have an important magnetic disturbance, and yet, at that very time, there might be no spots on the sun at all; that is to say, that the magnetic effect from the disturbance on the sun was of longer continuance than the visible appearance of the spot. It has therefore been of the utmost interest to me to find how the author has answered the question which arose in my mind after I had got thus far, but which I myself was quite unable to answer; that is to say, what becomes of the magnetic influence of the sun when it has reached the earth? In what way does it affect our atmosphere, and in what way does it disturb the magnetic condition here?

Mr. L. B. Atkinson: I feel that the author has filled in a gap that was left by Dr. Chree in his recent lecture on "Magnetic Storms" (*Journal I.E.E.*, 1919, vol. 57, p. 591). There are one or two questions I should like to ask the author. He speaks of the action of these currents of air which are moved by the sun and the tidal effects of the moon acting like the conductors of a dynamo on the magnetic fields of the earth. I should like to know whether in the view of those who have studied the subject the earth is viewed as revolving in a fixed field, or whether they regard that field as revolving with the earth. On this will depend whether there is or is not the electromotive force in the atmosphere in these higher layers, that is to say due to the rotation in this field, if it is fixed in space. Again, has any computation been made of the magnitude in amperes of these atmospheric currents for any given area? What are the approximate values in everyday units of these currents which produce magnetic disturbances?

Mr. E. H. Rayner: There are one or two electrical points which rather concern our present-day working on which I should like to ask a question or two. The first is a physical one. The author suggests that the ionization of the upper atmosphere is produced by the outward particles of helium; that these charge the upper atmosphere and come to the end of their career. I want to know what happens to that charge later. Is it slowly dissipated, following a sort of exponential time function, or is there some other negative impulse from the sun which in time may be expected to neutralize it? The other point is on this question of the auroral layer. The lantern slides have shown that there is a very sudden limit to the lower edge of the layer at which the aurora is seen. It seems likely to be closely related to our knowledge, such as it is, of what goes on in thermionic valves. If the author could give us any idea of what the actual pressure is, it would be extremely valuable. I do not ask for any close estimate; but can he say if it corresponds to a "hard" vacuum or a "soft" vacuum? Also can he give us any idea of the relative changes of pressure? I have never been able to ascertain from books what the pressure is, or if there is anything really known about it.

Mr. H. M. Sayers: The author states that the currents due to the diurnal magnetic changes occur at depths of 200 kilometres, and I should like to know how that has been measured. With regard to the magnitude of earth currents, mentioned by Mr. Atkinson, during magnetic disturbances these are apparently very great. I have seen all the north/south telegraph lines in this country absolutely stopped by these currents, which means that the voltage must have been of the order of 60 or 70 volts over 300 miles. A pressure of 60 or 70 volts across 300 miles of the earth's crust must have given currents corresponding to millions of amperes. The late Mr. Alexander Adams of the P. O. Telegraphs kept a record for many years of the earth currents observed on some of the principal lines running into the Central Telegraph Office. These were measured at the regular hour of daily tests, and might furnish useful information if analysed with the help of present knowledge. Some of the results were communicated to this Institution in papers some years ago.

Mr. G. M. B. Dobson: The author has suggested that the diurnal magnetic variation is due to tidal movements of the air. He has, no doubt, considered the effects of winds, but seeing that observations of the luminous streaks from meteors and of the dust from Krakatoa all show very strong winds at great heights, it is curious that those strong winds produce no noticeable magnetic effect, while the tidal movements of only a kilometre per hour give rise to the diurnal variations. The author has calculated from the radius of the maximum auroral zone that the particles injected from the sun must be α particles. Assuming this, one could presumably calculate the depth to which the particles would penetrate the atmosphere, i.e. the lower limit to the auroral layer. It would be valuable to know how well this agreed with the height found by direct observation.

Dr. C. Chree (*communicated*): In par. 2 the author says his "account is not limited to what can be regarded as certain conclusions . . . conjectural views have also been admitted." I must confess to a difficulty in recognizing what he regards as fact and what he regards as conjecture. The changes of magnetic force referred to in par. 1 cannot, I think, include the secular change. But, even so, the statement as to the ratio between the effects of atmospheric electric currents and secondary currents in the ground is one I consider largely if not entirely conjectural. The author has himself found such a ratio for the currents to which the Balfour Stewart–Schuster theory ascribes the regular diurnal variation. But this theory is not universally accepted, and other investigators accepting the theory provisionally have got different values for the ratio. Also, so far as I know, nothing distantly approaching an adequate investigation of the problem presented by irregular magnetic disturbance has yet been made. In par. 3 I understand the author to assert that the diurnal variations deduced from groups of quiet days and from groups of disturbed days are of quite distinct types, and in par. 11 this seems to form one of several arguments for the conclusion that the auroral layer is at a higher level than the layer in which circulate the electric currents originating the regular diurnal variation on quiet days. But this supposed

difference of type—while undoubtedly true of England—does not seem to apply everywhere. It is exceedingly inconspicuous, to say the least of it, in the records from the station of the Scott Antarctic Expedition of 1911–12. Practically we have there an intensification in disturbed days of the diurnal inequality characteristic of quiet days. On the other hand, the type of the regular diurnal inequality varies at most places with the season of the year. There are innumerable conjectures possible here, but, so far as I know, nothing approaching certainty. The atmospheric motions described in par. 6 are, I should surmise, wholly conjectural. I should suppose them to be inferences drawn by the author from the observed diurnal variation of barometric pressure at the earth's surface. At all events I cannot think of any other source of information. There are no clouds at the levels in question. The subject is one on which I should like to hear the opinion of the few meteorologists who have made a serious study of upper air phenomena. It is a "far cry" from the earth's surface to the upper confines of the atmosphere. In par. 8 the case for the α particles seems put too favourably. Störmer's calculations give for the *maximum* angular distance from the earth's magnetic axis attainable by α rays from the sun values between 10° and 19°, as compared with values of from 4° to 6° for β rays. But even 10° is less than the angular distance Störmer accepts for the most frequent occurrence of aurora, and much below the angular distance which aurora sometimes attains. Thus the difficulty which the author seems to consider fatal to the β-ray theory has not been satisfactorily removed even for the α-ray theory. The author's explanation of the so-called "sudden commencement" seen in some magnetic storms seems to overlook the fact that in high latitudes this movement is generally if not always oscillatory. Even at Eskdalemuir there is usually a fall in horizontal force prior to a more conspicuous rise. The author supposes the rise, which alone is usually seen in low latitudes, to be due to a downward movement of the upper atmosphere due to the impact of α rays. Does he ascribe the earlier of the two movements seen in high latitudes to an upward movement of the atmosphere, rising to greet the α rays? The above must serve as samples of the mental reservations I have been obliged to make when reading the paper.

Mr. P. R. Coursey (*communicated*): From a "wireless" point of view, the electrical phenomena in the upper levels of the atmosphere are of great importance as affecting the propagation of wireless signals over great distances, and the theory of such propagation. Although the author does not specifically discuss wireless matters in his paper beyond a bare mention, the consideration of both formation and dispersal of the ionized layers of the atmosphere would appear to be of special importance. Assuming that the lower layer of ionization referred to in the paper is due solely to ultra violet radiation from the sun during daylight hours, and that this layer breaks up during darkness, an explanation is at once forthcoming for the reduced and more irregular daylight signalling range, and for the much longer ranges obtained at night. During the day, the refraction of the wave through the lower layer, causing it to bend round the earth, would take place at a lower level in the atmosphere than the more regular reflection at the upper layer at night. It is therefore to be expected that the night range should be much greater than the day range. The author's conclusions as to the sharply defined lower surface of the upper layer are of particular interest in this connection. In connection with "atmospherics" or "X's," it would seem probable that the sudden changes in the electrical condition of the upper atmosphere caused by the impact of streams of charged particles would give rise to disturbances which would be detected in wireless receivers. The extremely sudden changes in the earth's magnetic force which occur at the commencement of and during a magnetic storm, as shown by the records exhibited during Dr. Chree's recent lecture, rather support this view. Some of those records also indicated oscillations of considerable frequency. In par. 11 of the present paper the author refers to the possible oscillations occurring when the electrostatic charges of the upper layer redistribute themselves. It may be that these oscillations would also be heard in wireless receivers. The usual types of X's heard show indications of having a very long wave-length—or a low oscillation frequency—which would agree with this conclusion in broad outline. In that case their direction of propagation would probably be radial to the earth, i.e. vertically downwards to the earth. In recent experiments in America it has been found that a certain class of X appears to be propagated in the vertical direction, and not in the horizontal one, as is usual for the ordinary signalling waves. This observation may support the above suggestion, or alternatively the same effect might be due to an induced oscillatory current or impulse in the surface layers of the earth consequent upon the same initial cause. In connection with the ionized layers and their effect upon signalling range, perhaps the author can suggest some explanation, from possible variations in the distribution of these layers, of the fact that the wireless range in the southern hemisphere (and particularly in the Pacific regions) is greater than in northern latitudes when using the same power.

Professor S. Chapman (*in reply*): Two speakers asked about the depth of penetration of these particles into the upper atmosphere, and the composition and pressure in the upper atmosphere in the auroral level. We know very little, from observation, about the pressure of the upper atmosphere beyond 25 or 30 kilometres, and beyond that point we have to infer the composition to a large extent. The only actual observational data bearing on it are spectroscopic data, and also the spectrum of the aurora. There are one or two uncertainties about the composition of the upper atmosphere. One is whether there is a large amount of hydrogen there. If there is, the pressure fall with height would be slower than if there is not. Personally I think hydrogen is not there; but whilst such an uncertainty remains there must be also a good deal of uncertainty as to the rate of diminution of pressure as we go upwards. However, one thing can be said with certainty, and that is that in the auroral layer the pressure must be exceedingly small. I think

I am not wrong when I say that it is of the order of one-millionth of an atmosphere. Whether that corresponds to what is known as a hard vacuum or a soft vacuum I cannot say. By some new calculations about the pressure and composition of the upper atmosphere, a colleague and I hope to test how far, on the most probable theories of the composition of the upper atmosphere, the depth of penetration agrees with the hypothesis that the corpuscles which enter the atmosphere from the sun are alpha particles.

As regards the effect of winds on the magnetic variations, it is quite true that the velocity of the wind far exceeds the small velocity of 1 kilometre per hour, viz. that of the tidal circulations to which, following Professor Schuster and Professor Balfour Stewart, I attribute the production of the daily magnetic variations. The reason why the winds are not important for the magnetic variation is because they occur in the troposphere, where the electric conductivity is such that, though electromotive forces are produced, they are ineffective and can impel only very weak electric currents. Not till we rise to considerable heights in the stratosphere where convection has ceased do we get sufficient conductivity to enable currents to flow, and there the only systematic motions present are these tidal motions of which I spoke.

A question was asked as to how we know that the earth currents associated with the daily magnetic variations flow at a depth below 200 kilometres. Roughly how we know is thus: We can separate by spherical harmonic analysis of the magnetic-variation field the parts respectively which originate in the atmosphere and below the earth's surface; we find that corresponding harmonic components from without and within have a certain ratio one to another; the outside ones are $2\frac{1}{2}$ or 3 times the amplitude of the internal ones, and there is a certain difference of phase angle between them. The internal currents reach their maximum before the external currents. There are thus two things to consider, a difference of phase and a difference of amplitude: it can be shown that if the earth were a uniformly conducting sphere the difference of phase and the relation of amplitude would not be as observed, and the most simple way in which the observed phase difference and amplitude ratio can be explained is by assuming a smaller radius for the conducting sphere, and that radius is about 200 kilometres smaller than the earth's radius. The surface earth currents have been investigated a little. The water-bearing strata near the earth's surface are doubtless as conducting as the layers beneath, but they are so thin that the currents which flow there in ordinary times are small in their effect owing to the thinness of the layer. When the external magnetic field is varying rapidly these magnetic variations cannot penetrate far into the surface. As is well known, rapidly alternating currents in a conductor flow near the surface, and the same thing occurs in the case of the earth. The rapidly varying magnetic field is shielded by large currents flowing near the surface of the earth; that is to say, in the surface stratum, about 5 miles deep, where water can penetrate, of course including the ocean. There is much scope for further investigation of surface earth-currents. I think the principle I have stated was not formerly recognized, and until that was done one could not expect to go very far in the scientific investigation of earth currents.

A question was asked as to what happens to the charges which come into the upper atmosphere. When they come into the atmosphere they charge the air, are brought to relative rest, and give rise to electrostatic forces of repulsion which overcome the force of gravity downwards on the air in which these charges are entangled. Consequently the charges escape upwards, and it is to that upward escape that I attribute the great diminution of the horizontal magnetic force during the magnetic storm. The length of time taken to escape depends upon the intensity of the original injection; the more intense the stream the more rapidly does the earth become charged, and the more rapidly does the charge escape. That is shown by the second phase of a magnetic storm, which proceeds most rapidly when the storm is most intense.

Mr. Atkinson asked whether the earth's magnetic field revolves with it, or whether the earth revolves in a stationary magnetic field. The main magnetic field of the earth revolves with the earth. We know that this is so because there are great local irregularities, and those local irregularities move with the earth. If at Greenwich the magnetic force points 15 degrees west of north, and in Russia it points truly north, one would expect, if the earth revolved in a stationary field, that when Greenwich got to where Russia was the compass direction would change from 15 degrees west of north to true north; but, of course, no such change as that takes place.

With regard to the magnitude, in ordinary units, of the currents in a given portion of the atmosphere during a storm, I have made the following estimate: In a storm which reduces the equatorial horizontal force by 100 *gamma*—not a very unusual amount—the corresponding current, flowing from east to west, is about 300 amperes for each kilometre measured north/south, at right angles to the current, near the equator.

I was much interested in the description Mr. Maunder gave of the reasoning and observations which led him to his discovery of this tendency of magnetic storms to recur after an interval equal to that taken by the sun to rotate. I owe very much to him and to others for the foundations of the theory here briefly and tentatively sketched; and these foundations will not suffer whatever the fate of this particular theory may be.

Mr. Reeves spoke about the slow secular change of magnetic force which continued for hundreds of years in the same direction. Those I have excluded from my paper, because I believe they are not due to these solar actions, except possibly very indirectly—I have made a suggestion about them in a recent paper, which I will not go into now. I cannot agree with Mr. Reeves's suggestion that the local irregularities of magnetic intensity have very much effect on the conformation of the auroral zone. The shape and radius of the auroral zone (if it is a zone and not a spiral) are probably determined by the earth's magnetic field over a distance of several diameters away from the earth, while these

local irregularities of magnetic intensity on the earth's surface cannot extend very far.

I have mentioned Professor Watson's investigation of the transmission of wireless waves round the earth. I have seen the result of his calculation, but have not yet read the actual paper itself. His calculation of conductivity is certainly not inconsistent with the magnetic data, but I think he has here provided a more definite item of information than can yet be gained or matched in other ways, about the exact height or conductivity of the electrically conducting zone in which the daily variations are produced. As to the lower limit of the auroral layer, its sharp limit is due, I think, to the sharp limit of penetration of the outer particles. Doubtless the part immediately below is to some extent conducting, because these outer particles in their passage through the atmosphere may knock electrons off the surrounding molecules, and some of these electrons will diffuse into the space below, so that the conductivity will not drop suddenly.

With regard to Dr. Eccles' remarks about wireless telegraphy, I am very glad to find how far these magnetic investigations have corroborated results obtained in quite a different way. In the paper I deal only with two layers, the auroral layer and a layer beneath, which is ionized by ultra-violet light, and does not lose its ionization during the course of the night. The lower atmosphere, which also seems to affect "wireless" transmission, is of less interest for students of terrestrial magnetism. As Dr. Eccles remarks, I should suppose that Austin's formula is related to the lower ionized layer produced by ultra-violet light.

(*Communicated*): Through misunderstanding Mr. Dobson's question, my reply referred only to the ordinary tropospheric winds. I am aware that meteor observers have seen meteor trails changing shape, thus indicating the presence of winds at great heights; a careful discussion of such observations, including a critical study of the corresponding height-determinations, would be a valuable contribution to our scanty knowledge of the upper atmosphere. The only data concerning variable meteor trails which I have seen (through the kindness of Mrs F. Wilson, F.R.A.S.) suggested that the associated winds were very inconstant. Such winds, if present in the ionized layers, would produce magnetic effects of a local kind, which it is certainly not possible to say are not shown on magnetographs. The magnetic variations offer a wide field of investigation, of which only the fringe has been touched; the diurnal variations and the world-wide large disturbances are the two outstanding features I have dealt with, and their main causes appear to me to be as I have stated in my paper. Variable winds may produce subsidiary effects which have not yet been recognized, and the same is true of constant winds (not diurnal), for the latter would simply add to the local variations in the earth's "permanent" magnetic field. The causes of these local variations are certainly partly below the earth's surface, but may also be partly atmospheric.

In his written communication Dr. Chree has specified various points which, as I agree, cannot be regarded as "certain conclusions." The important question as to the value and probability of these particular conjectures can be finally settled only by further study, as to the need of which I am at one with him; new facts and considerations will inevitably necessitate modifications or extensions of these hypotheses. In a subject with so many ramifications it cannot be expected that, even if all the facts were known, a complete theory could be provided all at once; and perhaps I differ chiefly from Dr. Chree in thinking it advisable to construct hypotheses on the basis of what seem to be the outstanding facts now known. Some of the particular points mentioned by him are discussed in the paper cited in par. 11, which will shortly appear in the *Cambridge Philosophical Transactions*: the effect of disturbance on the diurnal magnetic variations in polar regions is, I think, there accounted for. The theory of the auroral zone, and the nature of the injected particles, are undeniably subject to revision. As regards "sudden commencements" (referring to Dr. Chree's last question) the suggested explanation of their oscillatory nature in high latitudes is, of course, not one which could reasonably be propounded.

Mr. Coursey's mention of vertically-propagated wireless waves is very interesting, and it may be that these arise in the magnetic disturbance and auroral layer. If so, they should be more intense by night than by day.

THE SPARKING VOLTAGES BETWEEN SPHERICAL ELECTRODES.*

By Dr. Alexander Russell, Member.

(*Paper received 22 September*, 1919.)

In the paper on "The Grading of Cables" which the author read before the Institution in 1908, short tables were given by means of which the maximum electric stress between two spherical electrodes could be computed at the instant of discharge, whatever the potentials of the spheres might be. These tables have been used by several experimenters. In practice the sparking potentials are either found by fixing the spark-gap and gradually increasing the voltage until the spark ensues, or by keeping the potential difference constant and slowly bringing the electrodes nearer to one another. Using either of these methods practically constant values have been obtained for the maximum electric stress at the instant of discharge, provided that the potentials of the spheres are equal and opposite. When the requisite corrections for the temperature and pressure of the air are applied, the results obtained by different experimenters practically agree, the maximum inaccuracy being about 1 per cent. When the electrodes are further apart than 1 mm. the maximum electric stress at a given pressure and temperature of the air depends only on the size of the electrodes, being very great for small spheres and approaching a limiting value of about 27·5 kilovolts per centimetre for large spheres when the temperature is 25° C. and the height of the barometer is 76 cm.

When one of the electrodes is earthed, then apparently in some cases the maximum electric stress is not constant but increases as the length of the spark-gap increases.

It is desirable therefore to investigate and see whether some simple formula can be found which will give the value of the maximum electric stress when the potentials are equal and opposite, as this will enable us to calculate the sparking voltages between any sized spherical electrodes whatever their distance apart may be. It is desirable also to consider possible causes which would explain the results obtained when one of the electrodes is earthed.

New experimental results are not given in this paper but the results obtained by A. Heydweiller† 26 years ago and the results published in the "Standardization Rules of the American Institute of Electrical Engineers" (1918) are examined and various deductions are made from them. Many other experimental results might have been chosen as the groundwork of our analysis, but these were chosen as being perhaps the best known to electricians. Most of the other experimental results, however, lead to the same conclusions.

* The Papers Committee invite written communications (with a view to publication in the *Journal* if approved by the Committee) on papers published in the *Journal* without being read at a meeting. Communications should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† "Entladungspotentiale," *Annalen der Physik und Chemie*, 1893, vol. 48, p. 235.

Formulæ for the Maximum Electric Stress Between Equal Spherical Electrodes.

If the radii of the spherical electrodes be each equal to a, and E_1 and E_2 be their potentials, than if x be the distance between them, the value of the maximum electric stress on the dielectric is given by*

$$R_{max.} = \frac{E_1 - E_2}{x} f_1 + \frac{2\,E_2}{x}(f_1 - f) \quad . \quad . \quad (1)$$

where $f = \sinh\alpha \cosh(\alpha/2)$

$$\left\{ \frac{\sinh(\alpha/2)}{\cosh^2(\alpha/2)} + \frac{\sinh(3\alpha/2)}{\cosh^2(3\alpha/2)} + \frac{\sinh(5\alpha/2)}{\cosh^2(5\alpha/2)} + \ldots \right\}$$

$$f_1 = 2\sinh\alpha \cosh(\alpha/2)$$

$$\left\{ \frac{\sinh(\alpha/2)}{\cosh^2(\alpha/2)} + \frac{\sinh(5\alpha/2)}{\cosh^2(5\alpha/2)} + \frac{\sinh(9\alpha/2)}{\cosh^2(9\alpha/2)} + \ldots \right\}$$

and $\cosh\alpha = 1 + x/(2a)$.

When the potentials of the spheres are equal and opposite

$$E_1 = -E_2 = \frac{E_1 - E_2}{2}$$

and hence by (1), $$R_{max.} = \frac{E_1 - E_2}{x} f \quad . \quad . \quad . \quad (2)$$

When $E_2 = 0$, we have similarly,

$$R_{max.} = \frac{E_1}{x} f_1 \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The values of f and f_1 are determined accurately by the formulæ given above. The computation, however, is very laborious, especially when x is small. To simplify the calculation of these qualities the following formulæ have been obtained.

Calculation of f.—When x/a is not greater than 0·8 we can use the formula

$$f = 1 + \frac{1}{3}\cdot\frac{x}{a} + \frac{1}{45}\cdot\frac{x^2}{a^2} + \frac{2}{945}\cdot\frac{x^3}{a^3} + \frac{17}{14175}\cdot\frac{x^4}{a^4}$$

The maximum inaccuracy introduced by using this formula occurs when $x/a = 0{\cdot}8$ and it is then about 1 in 2,000. For values of x/a less than 0·5 it is accurate enough for all practical purposes.

* A. Russell, "Alternating Currents," vol. 1, p. 258.

When x/a is greater than 0·8 we can use the formula

$$f = \frac{1}{2}\frac{x}{a} - 1\left(\frac{x}{a}\right)^2 + \frac{1}{x/a + 2} - \frac{x/a}{2(x/a + 2)^2} + \frac{x/a}{2(x/a + 2)^3} - \frac{x/a}{2(x/a + 2)^4} - \frac{x/a}{2(x/a + 2)^5} - \frac{2x/a}{(x/a + 2)^5}$$

When x/a equals 0·8 the error introduced by using this formula is about 1 in 2,000, but it diminishes very rapidly as x/a increases.

Calculation of f_1.—When x/a is not greater than $\frac{1}{4}$, $f_1 = f$.

When x/a lies between $\frac{1}{4}$ and 1,

$$f_1 = 0{\cdot}0465 + \frac{1}{a} + \frac{1}{1 + x/a} - 0{\cdot}03\,a$$

and when x/a is not less than unity,

$$f_1 = \frac{x}{a} - \frac{1}{x/a + 1} + \frac{1}{(x/a - 1)(x/a + 2)^3}$$

The second of these formulæ is purely empirical. Nearly all the calculations made in this paper were computed by these approximate formulæ.

Sparking Voltages in Air.

The experimental results given in the next three tables were obtained by A. Heydweiller in 1893 (*l.c. ante*). He experimented with equal spherical electrodes, the diameters being 0·5, 1 and 2 cm. respectively. It has to be remembered that what happens when the spark-gap is less than 1 mm. is not considered in this paper.

Table 1.

Two equal spheres. Radius = a = 0·25 cm. Both insulated. Temperature = θ = 18° C. Barometric height = h = 71·5 cm. E = maximum sparking pressure between the electrodes.

E Kilovolts	Spark-gap, x, in cm.	$\frac{x}{a}$	f	$R_{max.} = E/x\,f$
4·130	0·1	0·4	1·137	54·0
8·370	0·2	0·8	1·283	53·7
11·34	0·3	1·2	1·437	54·3
13·77	0·4	1·6	1·599	55·1
15·72	0·5	2·0	1·770	55·7
17·19	0·6	2·4	1·945	55·7
18·30	0·7	2·8	2·124	55·5
19·02	0·8	3·2	2·306	54·8
20·19	1·0	4·0	2·678	54·1
22·35	1·5	6·0	3·632	54·1

The mean value of $R_{max.}$ for spheres $\frac{1}{2}$ cm. in diameter is therefore 54·2 kilovolts per cm. The mean potential gradients vary from 48·3 to 14·88, but when multiplied by the correcting factor f they give practically the same number. As f is calculated from purely geometrical data, these results verify the theory.

Table 2.

Two equal spheres. Radius = a = 0·5 cm. Spheres insulated. Temperature = θ = 18° C. Barometric height = h = 74·5 cm.

E Kilovolts	Spark-gap, x, in cm.	$\frac{x}{a}$	f	$R_{max.} = E/x\,f$
4·80	0·1	0·2	1·068	51·3
8·37	0·2	0·4	1·137	47·6
11·37	0·3	0·6	1·200	45·8
14·55	0·4	0·8	1·283	40·7
17·31	0·5	1·0	1·359	47·1
19·02	0·6	1·2	1·437	47·7
22·05	0·7	1·4	1·515	47·7
24·09	0·8	1·6	1·599	48·2
25·59	0·9	1·8	1·685	47·0
27·00	1·0	2·0	1·770	47·5

As the first result is obviously too high we neglect it. The mean value of $R_{max.}$ for the nine remaining results is 47·4 kilovolts per centimetre. Using this value we find that E for 1 mm. spark-gap is 4·44 kilovolts. For spheres of half the size we see from Table 1 that for a millimetre spark-gap the pressure was 4·83 kilovolts. The smaller electrodes therefore require an appreciably higher sparking voltage for 1 mm. gap.

Table 3.

Two equal spheres. Radius = a = 1 cm. Spheres insulated. Temperature = θ = 18° C. Barometric height = h = 74·5 cm.

E Kilovolts	Spark gap, x, in cm.	$\frac{x}{a}$	f	$R_{max.} = (E/x)f$
4·710	0·1	0·1	1·034	48·7
8·100	0·2	0·2	1·068	43·3
11·37	0·3	0·3	1·102	41·8
14·49	0·4	0·4	1·037	41·2
17·49	0·5	0·5	1·173	41·0
20·37	0·6	0·6	1·200	41·0
23·25	0·7	0·7	1·245	41·3
26·04	0·8	0·8	1·283	41·8
31·29	1·0	1·0	1·359	42·5
35·49	1·2	1·2	1·437	42·5
38·64	1·4	1·4	1·515	41·8
41·28	1·6	1·6	1·599	41·3

Neglecting the first result we get 41·7 for the mean value of $R_{max.}$ Substituting this value in the formula $E = R_{max.}\,(x/f)$, we find that for 1 mm. gap the sparking pressure is 4·04 kilovolts, which is less than in either of the preceding cases.

We shall now analyse the results given in the "Standardization Rules" of the American Institute (1918), page 55

TABLE 4.

Two equal spheres. Radius = $a = 3{\cdot}125$ cm. Both insulated. Temperature = $\theta = 25°$ C. Barometric height = $h = 76$ cm. $E/\sqrt{2}$ = effective kilovolts.

$E/\sqrt{2}$ Kilovolts	Spark-gap, x, in cm.	$\frac{x}{a}$	f	$R_{max.} = (E/x)f$
10	0·42	0·1344	1·045	35·2
20	0·86	0·2752	1·093	35·9
30	1·35*	0·4320	1·148	36·1
40	1·92	0·6144	1·213	35·7
50	2·50	0·8000	1·283	36·3
60	3·20	1·024	1·372	36·4
70	3·95	1·264	1·462	36·6
80	4·90	1·568	1·588	36·7
90	6·05	1·936	1·743	36·7

The mean value of $R_{max.}$ found from this table is 36·2.

TABLE 5.

Two equal spheres. Radius = $a = 6{\cdot}25$ cm. Both insulated. Temperature = $\theta = 25°$ C. Barometric height = $h = 76$ cm. $E/\sqrt{2}$ = effective kilovolts.

$E/\sqrt{2}$ Kilovolts	Spark-gap, x, in cm.	$\frac{x}{a}$	f	$R_{max.} = (E/x)f$
30	1·41	0·2256	1·076	32·4
40	1·91	0·3056	1·104	32·7
50	2·44	0·3904	1·134	32·9
60	3·00	0·4800	1·165	33·0
70	3·60	0·5760	1·199	33·0
80	4·20	0·6720	1·234	33·2
90	4·90	0·7840	1·275	33·1
100	5·50	0·8800	1·311	33·7
120	7·10	1·136	1·412	33·8
140	8·80	1·408	1·521	34·2
160	11·0	1·760	1·668	34·3
180	13·8	2·208	1·861	34·3

The mean value of $R_{max.}$ for spherical electrodes of radius 6·25 cm. is therefore 33·4. It will be seen that the values of $R_{max.}$ increase slightly as the gap is increased. This is probably due to a slight want of symmetry between the two sides of the sparking apparatus. It has to be remembered that in calculating $R_{max.}$ we must take the maximum value E for the pressure and not the effective value $E/\sqrt{2}$.

It is necessary to consider whether we are justified in assuming that the potentials of the spheres are equal and opposite. With direct voltage the leakage currents determine the potentials. Hence if the insulation resistance of each side of the supply is the same, the symmetry shows us that the potentials of the electrodes must be equal and opposite.

With alternating voltage we have also to take the capacities of the electrodes into account. We can exactly imitate the effects of the capacities of two equal spheres in space by assuming that they have no capacity but are joined directly by a condenser of capacity $-k_{12}$ and are each connected to earth by a condenser $k_{11} + k_{12}$, where k_{11} and k_{12} are the self and mutual capacity coefficients. These coefficients can be readily calculated.* For instance when the spheres of radius 6·25 cm. are 3·125 cm. apart, so that x/a is 0·5, we find that

$$k_{11} + k_{12} = 4{\cdot}55 \text{ cm.} = 4{\cdot}55/(9 \times 10^5) \text{ mfd.}$$
$$-k_{12} = 3{\cdot}28 \text{ cm.} = 3{\cdot}28/(9 \times 10^5) \text{ mfd.}$$

It is also easy to see that the value of $k_{11} + k_{12}$ varies slowly as x increases.

If the potential difference of an electrode to earth was 100 kilovolts, and the frequency were 50, then the capacity current to earth would be

$$2\pi \times 50\{4{\cdot}55/(9 \times 10^5)\}10^5 \times 10^{-6}$$

which equals 0·00016 of an ampere approximately. If the leakage currents be much smaller than this then the potentials of the spheres will be equal and opposite, their values being determined by the capacity currents.

It has to be remembered, however, that if one of the electrodes is nearer to a wall than the other, then the capacity coefficients of the two spheres are different and their potentials will no longer be equal and opposite. Even the presence of an experimenter in the neighbourhood of a sphere will alter its coefficients, the values of the artificial condensers connecting them to earth becoming $k'_{11} + k'_{12}$ and $k'_{22} + k'_{12}$ respectively. The ratio of the potentials of the electrodes will numerically be inversely as these capacities when the leakage currents are negligibly small. We shall return to this point when we discuss the experimental results obtained with one electrode earthed.

TABLE 6.

Two equal spheres. Radius = $a = 12{\cdot}5$ cm. Both insulated. Temperature = $\theta = 25°$ C. Barometric height = $h = 76$ cm. $E/\sqrt{2}$ = effective kilovolts.

$E/\sqrt{2}$ Kilovolts	Spark-gap, x, in cm.	$\frac{x}{a}$	f	$R_{max.} = (E/x)f$
60	2·9	0·232	1·079	31·6
70	3·5	0·280	1·095	31·0
80	4·1	0·328	1·113	30·7
90	4·5	0·360	1·123	31·8
100	5·1	0·408	1·140	31·6
120	6·3	0·504	1·174	31·6
140	7·7	0·616	1·214	31·2
160	9·0	0·720	1·252	31·5
180	10·6	0·848	1·299	31·2
200	12·3	0·984	1·352	31·1
220	14·1	1·128	1·409	31·1
240	16·0	1·280	1·470	31·3
260	18·0	1·440	1·535	31·4
280	20·3	1·624	1·611	31·4
300	23·1	1·848	1·705	31·3
320	26·5	2·120	1·823	31·1

The mean value of $R_{max.}$ is 31·3 kilovolts per centimetre and the constancy of the values for $R_{max.}$ shows how carefully the experiments were made.

* As given in earlier editions. The value 1·41 given in the 1918 edition makes $R_{max.}$ 34·5.

* 'Alternating Currents," vol. 1, p. 243.

TABLE 7.

Two equal spheres. Radius = a = 25 cm. Both insulated.
Temperature = θ = 25° C. Barometric height = 76 cm.

E.s.v. kilovolts	Spark gap, s, in cm.	$\frac{s}{a}$	f	$R_{max.} = (E/s)f$
80	4·1	0·164	1·055	29·1
90	4·5	0·180	1·061	30·0
100	5·1	0·204	1·069	29·6
120	6·2	0·248	1·084	29·7
140	7·3	0·292	1·099	29·8
160	8·3	0·332	1·113	30·3
180	9·5	0·380	1·130	30·3
200	10·6	0·424	1·145	30·6
220	11·7	0·468	1·161	30·9
240	13·0	0·520	1·179	30·8
260	14·4	0·576	1·199	30·6
280	15·8	0·632	1·220	30·6
300	17·1	0·684	1·238	30·7
320	18·7	0·748	1·261	30·5
340	20·4	0·806	1·283	30·2
360	22·1	0·884	1·312	30·2
380	23·9	0·956	1·341	30·2
400	25·7	1·028	1·372	30·2

The mean value of $R_{max.}$ is 30·2 kilovolts per centimetre, and the analysis again shows the accuracy of the experimenters.

CORRECTING FOR TEMPERATURE AND PRESSURE.

The value of $R_{max.}$ for air depends on the temperature and pressure, being greater the lower the temperature and the higher the pressure. If $R_{max.}$ be the sparking potential gradient at 25° C. and 76 cm. pressure, and $R'_{max.}$ be the sparking potential gradient at θ° C. and h cm. pressure, we have

$$R'_{max.} = \frac{3{\cdot}92\,h}{273+\theta} R_{max.} \quad \text{and} \quad R_{max.} = \frac{273+\theta}{3{\cdot}92\,h} R'_{max.}$$

For example, to convert the mean values of $R_{max.}$ deduced from Heydweiller's experiments into their values at 25° C. and 76 cm. pressure we multiply them by 2·01 (3·92 × 74·5), that is, by 0·9964. Hence we find that the mean values of $R_{max.}$ at 25° C. and 76 cm. pressure for spheres whose radii are ¼, ½ and 1 cm. respectively are 54·6, 47·2 and 41·5.

The author has found that the formula

$$R_{max.} = 27{\cdot}4 + 14{\cdot}1/\sqrt{a} \quad . \quad . \quad . \quad (4)$$

is very approximately correct for spherical electrodes varying in radius from ¼ to 25 cm. For instance, the following table shows how the experimental results given above compare with the values computed by this formula

It will be seen that the agreement is quite satisfactory. In experiments on spark voltages, the electrodes are generally put at a fixed distance apart and the voltage is gradually increased until the spark takes place. Before the spark ensues we have convection currents of electrified air flowing past the electrodes.

When we have a hot sphere in cold air the heat carried away by the convection currents per square centimetre of surface is greater for small spheres than for large ones. Similarly the electricity carried away per square centimetre of the electrodes by the air convection currents is greater for small than for large spheres. We know in the case of the hot sphere that the heat per square centimetre carried away by the convection currents varies as $1/a^{\frac{1}{4}}$, where a is the radius of the sphere. Pursuing the analogy, the electricity per square centimetre carried away by the convection currents flowing round the spheres will also vary as $1/a^{\frac{1}{4}}$ and this tending to prevent an electric discharge will introduce a term $B/a^{\frac{1}{4}}$ into the value of $R_{max.}$ the force required to produce the discharge. The force required to break down the air itself will be constant. Hence we may assume that

$$R = A + B/\sqrt{a}$$

and determine as we have done above the values of A and B.

It will be noticed that formula (4) is very nearly identical with the formula

$$R_{max.} = 27{\cdot}2 + \frac{14{\cdot}7}{\sqrt{a}}$$

given by F. W. Peek in his book on "Dielectric Phenomena."

The formula being undoubtedly very approximately true, it will be useful to construct by its help a table of the sparking distances between equal spheres 1 inch in diameter and also between equal spheres 10 cm. in diameter as these values are often used in practice. For 1-inch electrodes,

$$R_{max.} = 27{\cdot}4 + \frac{14{\cdot}1}{\sqrt{1{\cdot}27}} = 39{\cdot}9 \text{ kilovolts per cm.} = 101{\cdot}4 \text{ kilovolts per inch.}$$

For 10-cm. electrodes,

$$R_{max.} = 27{\cdot}4 + \frac{14{\cdot}1}{\sqrt{5}} = 33{\cdot}71 \text{ kilovolts per cm.}$$

The values of E are equal to $(s/f)\,R_{max.}$

E_1 denotes the sparking potential between the spheres when one of them is at zero potential. In this case

$$E_1 = (s/f_1)\,R_{max.}$$

Radius a in cm	0·25	0·5	1	3·125	6·25	12·5	25
$R_{max.}$ (observed) . .	54·6	47·2	41·5	36·2	33·4	31·3	30·2
$R_{max.}$ (calculated) . .	55·6	47·3	41·5	35·4	33·2	31·4	30·2

TABLE 8.

Two equal spheres. Radius = a = 0·5 inch. Temperature = θ = 25° C. Barometric pressure = h = 76 cm. E = sparking pressure in kilovolts when both spheres insulated. E_1 = sparking pressure in kilovolts when one sphere is at zero potential. $R_{max.}$ = 101·4 kilovolts per inch.

Spark-gap, x, in inches	$\frac{x}{a}$	f	f_1	E	E_1
0·1	0·2	1·068	1·068	9·50	9·50
0·2	0·4	1·137	1·150	17·8	17·6
0·3	0·6	1·209	1·253	25·2	24·3
0·4	0·8	1·283	1·378	31·6	29·4
0·5	1·0	1·359	1·517	37·3	33·4
0·75	1·5	1·559	1·909	48·8	39·8
1·0	2	1·770	2·339	57·3	43·3
1·5	3	2·215	3·252	68·7	46·8
2·0	4	2·678	4·201	75·7	48·3
2·5	5	3·151	5·167	80·5	49·1
3·0	6	3·632	6·143	83·8	49·5

If the disruptive voltage for a 3-inch gap were 30 times that for a 0·1-inch gap it would equal 285 kilovolts. Its actual value is 83·8 kilovolts when the potentials are equal and opposite, that is, when they are 41·9 and − 41·9 kilovolts respectively. This gap would also break down when one of the electrodes was at 49·5 kilovolts and the other was maintained at zero potential.

TABLE 9.

Two equal spheres. Radius = a = 5 cm. Temperature = θ = 25° C. Barometric height = h = 76 cm. E = sparking pressure in kilovolts, both spheres insulated. E_1 = sparking pressure in kilovolts, one sphere at zero potential. $R_{max.}$ = 33·71 kilovolts per centimetre.

Spark-gap, x, in cm.	$\frac{x}{a}$	f	f_1	E	E_1
0·5	0·1	1·034	1·034	16·3	16·3
1·0	0·2	1·068	1·068	31·6	31·6
1·5	0·3	1·102	1·106	45·9	45·7
2·0	0·4	1·137	1·150	59·3	58·6
3·0	0·6	1·209	1·253	83·7	80·7
4·0	0·8	1·283	1·378	105·2	97·8
5·0	1·0	1·359	1·517	124·1	111·1
7·5	1·5	1·559	1·909	162·2	132·4
10·0	2	1·770	2·339	190·4	144·1
20·0	4	2·678	4·201	251·8	160·5
30·0	6	3·632	6·143	278·5	164·6

For instance, we see from Table 9 that with 10-cm. electrodes when the distance between them is 7·5 cm. a spark discharge ensues when the potentials of the electrodes are 81·1 and − 81·1 kilovolts respectively, and also when they are at potentials 132·4 kilovolts and zero respectively. For sine-shaped waves the effective values of the sparking voltages are $E/\sqrt{2}$ and $E_1/\sqrt{2}$ respectively.

SIZE OF ELECTRODES WHICH REQUIRE THE HIGHEST VOLTAGE FOR A GIVEN SPARK-GAP.

Using the formula (4) for $R_{max.}$ we have constructed Table 10.

Looking along the horizontal column for a spark-gap of 0·2 cm. it will be seen that the sparking voltage continually diminishes as the size of the electrodes is increased, beginning with electrodes of radii each equal to $\frac{1}{4}$ cm. For equal electrodes of radii 0·1 cm. the sparking pressure for this air-gap would be 8·1 kilovolts. It will be seen therefore that for electrodes of a certain size of radius lying in value between 0·1 and 0·5, the sparking voltage for an air-gap of 0·2 cm. has a maximum value. For the other gaps given in the table it will be seen directly that a similar theorem holds.

When the air-gap is greater than 0·7 cm. it is not difficult to calculate the size of the electrodes which make the sparking voltage a maximum. In this case we may write

$$E = \frac{x\,(27{\cdot}4 + 14{\cdot}1/\sqrt{a})}{1 + x/3a + x^2/(45\,a^2)}$$

Equating $\frac{\partial E}{\partial a}$ to zero, we get

$$7{\cdot}05\,(45\,a^2 + 15\,a\,x + x^2) = x\,(15\,a + 2\,x)\,(27{\cdot}4\,a^{\frac{1}{2}} + 14{\cdot}1)$$

The positive value of a which satisfies this equation makes E a maximum, provided that it does not make x/a greater than a half. This is ensured if x be greater than 0·7.

As a numerical example, let us put $x = 1$. The equation becomes

$$7{\cdot}05\,(45\,a^2 + 15\,a + 1) = (15\,a + 2)\,(27{\cdot}4\,a^{\frac{1}{2}} + 14{\cdot}1)$$

By substituting, for a, 2 and 3 respectively we see that the root must lie between these values; for 2 makes the right-hand side the greater whilst 3 makes it the smaller. Assuming that $a = 2{\cdot}5$ is an approximate root and applying Newton's theorem, we find that $a = 2{\cdot}53$ satisfies the equation very approximately. The value of E in this case is 31·96. Since 1/2·53 is less than 0·5 we are justified in assuming that f equals

$$1 + x/(3\,a) + x^2/(45\,a^2)$$

Hence when the air-gap is 1 cm. the sparking voltage is a maximum for spherical electrodes whose diameters are each equal to 5·06 cm., which is practically 2 inches.

By using the approximate formulæ given for f we could find in a similar way the spherical electrodes which make the sparking voltages a maximum for air-gaps less than 0·7 cm. They can, however, easily be found graphically by plotting the values of (x/f) $R_{max.}$ against the radii of the electrodes.

TABLE 10.

Sparking Pressures in Kilovolts for Various Sized Electrodes for Gaps of 0·2, 0·5, 1, 1·5 and 2 cm respectively.

Spark length	0·25	0·5	1·0	3·125	5	6·25	12·5	25	44	Radii
0·2	8·7	8·3	7·8	7·1	6·7	6·6	6·2	6·1	5·5	Pressure in kilovolts
0·5	15·7	17·4	17·7	16·8	16·3	16·2	15·5	15	13·7	
1·0	26·8	26·7	30·5	31·9	31·6	31·5	30·6	29·8	27·2	
1·5	32·3	32·0	39·9	45·6	45·9	46·1	45·3	44·1	41·0	
2·0	34·2	35·3	46·8	57·3	59·3	59·9	59·6	58·8	54·8	

ONE ELECTRODE EARTHED

We shall now consider the experimental results given in the American "Standardization Rules" when one electrode is earthed

TABLE 11

Two equal spheres. Radius = a = 25 cm. One earthed. $E_2 = 0$. Temperature = θ = 25° C. Barometric height = h = 76 cm. $E_1/\sqrt{2}$ = effective kilovolts.

$E_1\sqrt{2}$ (Kilovolts)	Sparking distance (cm)	$\frac{s}{a}$	f	$R_{obs} = \frac{E_1}{E_1 - E_2} f_1$
80	4·1	0·164	1·055	29·1
90	4·6	0·184	1·062	29·4
100	5·2	0·208	1·070	29·1
120	6·3	0·252	1·088	29·3
140	7·4	0·296	1·105	29·6
160	8·5	0·340	1·123	29·9
180	9·7	0·388	1·143	30·0
200	10·8	0·432	1·168	30·5
220	12·0	0·480	1·188	30·8
240	13·3	0·532	1·215	31·0
260	14·8	0·592	1·240	31·0
280	16·3	0·652	1·284	31·2
300	17·7	0·708	1·319	31·6
320	19·4	0·776	1·362	31·8
340	21·4	0·856	1·416	31·8
360	23·4	0·936	1·471	32·0
380	25·5	1·020	1·531	32·2
400	27·6	1·104	1·595	32·7

It will be seen that the values of R_{obs} are not constant but increase gradually in value from about 29·1 to 32·7. As the experiments were carefully made there must be some reason for this increase. A water-tube resistance of about 1 ohm per volt was probably inserted in series with the insulated electrode so as to damp the high-frequency oscillations at the time of breakdown; and one feels that the current which will flow through this resistance might be of importance. But not enough, in our opinion, to have any appreciable effect.

Before discussing other possible causes let us make the assumption that the potentials of the electrodes at the instant of breakdown, instead of being E_1 and zero, are E_1 and E_2, so that $E_1 - E_2$ is the sparking pressure. We shall also make the assumption that the ratio $\frac{E_2}{E_1}$ is constant. We may therefore write

TABLE 12.

Two equal spheres. Radius = a = 25 cm. $E_2 = -0·43(E_1 - E_2)$. $m = 0·43$.

$(E_1 - E_2)\sqrt{2}$ Kilovolts	Spark length, in cm	f	f_1	$k = \frac{E_1 - E_2}{2m(E_1 - E_2)} f(f - f_1)$
80	4·1	1·055	1·055	29·1
90	4·6	1·062	1·062	29·4
100	5·2	1·070	1·070	29·1
120	6·3	1·086	1·088	29·3
140	7·4	1·101	1·105	29·5
160	8·5	1·110	1·123	29·8
180	9·7	1·133	1·143	29·8
200	10·8	1·148	1·164	30·2
220	12·0	1·165	1·188	30·3
240	13·3	1·184	1·215	30·6
260	14·8	1·200	1·240	30·4
280	16·3	1·227	1·284	30·4
300	17·7	1·248	1·319	30·6
320	19·4	1·263	1·362	30·5
340	21·4	1·304	1·416	30·3
360	23·4	1·335	1·471	30·2
380	25·5	1·367	1·531	30·1
400	27·6	1·400	1·595	30·2

This value gives the same value of $k_{max} = 30·6$. This compares with 32·7 when the potentials are equal and opposite.

$E_2 = -m\ (E_1 - E_2)$ where m is a constant. In this case we get, by (1)

$$R_{max.} = \frac{E_1 - E_2}{x} f_1 - \frac{2m\ (E_1 - E_2)}{x} (f_1 - f)$$

There are two unknowns in this equation, $R_{max.}$ and m, we therefore need two experimental results to determine them. Taking the experimental results for sparking pressures of 200 and 400 kilovolts respectively from the table given above, we get

$$R_{max.} = 30{\cdot}5 - m\ (400/10{\cdot}8)\ (0{\cdot}016)$$

and $$R_{max.} = 32{\cdot}7 - m\ (800/27{\cdot}6)\ (0{\cdot}195)$$

Solving these equations we find that

$$R_{max.} = 30{\cdot}2 \text{ and } m = 0{\cdot}4348$$

This value of $R_{max.}$ is the same as the mean result obtained when the potentials of the spheres were equal and opposite. It will therefore be of interest to see what value we get for $R_{max.}$ from the other experiments on the assumption that $m = 0{\cdot}43$ whatever the distance apart of the electrodes.

If all the tests were made with the same apparatus then it is probable that m is approximately equal to 0·43 in all cases. We shall make this assumption.

TABLE 13.

Two equal spheres.

Radius $= a = 12{\cdot}5$ *cm.*

$E_2 = -0{\cdot}43\ (E_1 - E_2)$; $E_1 = 0{\cdot}57\ (E_1 - E_2)$;

$$R_{max.} = \frac{E_1 - E_2}{x} f_1 - \frac{0{\cdot}86\ (E_1 - E_2)}{x} (f_1 - f)$$

$(E_1-E_2)\sqrt{2}$ Kilovolts	Spark-gap, x, in cm.	$\frac{x}{a}$	f	f_1	$\frac{E_1-E_2}{x} f_1$	$R_{max.}$
60	2·9	0·232	1·079	1·080	31·6	31·6
70	3·5	0·280	1·095	1·099	31·1	31·1
80	4·1	0·328	1·113	1·118	30·8	30·7
90	4·6	0·368	1·126	1·134	31·4	31·3
100	5·2	0·416	1·143	1·156	31·5	31·3
120	6·4	0·512	1·177	1·205	32·0	31·5
140	7·8	0·624	1·217	1·267	32·2	31·4
160	9·2	0·736	1·258	1·336	32·9	31·7
180	10·9	0·872	1·310	1·427	33·3	31·7
200	12·8	1·024	1·373	1·534	33·9	31·7
220	15·0	1·200	1·437	1·668	34·6	31·7
240	17·7	1·416	1·525	1·840	35·3	31·6
260	21·0	1·680	1·633	2·061	36·1	31·5
280	25·0	2·000	1·770	2·339	37·1	31·6

The mean value of $R_{max.}$, therefore, is 31·5 kilovolts per centimetre. This compares with 31·3 given by Table 6.

TABLE 14.

Two equal spheres.

Radius $= a = 6{\cdot}125$ *cm.*

$$R_{max.} = \frac{E_1 - E_2}{x} f_1 - \frac{0{\cdot}86\ (E_1 - E_2)}{x} (f_1 - f).$$

$(E_1-E_2)\sqrt{2}$ Kilovolts	Spark-gap, x, in cm.	$\frac{x}{a}$	f	f_1	$\frac{E_1-E_2}{x} f_1$	$R_{max.}$
30	1·41	0·2256	1·077	1·077	32·4	32·4
40	1·91	0·3056	1·104	1·109	32·4	32·4
50	2·44	0·3904	1·134	1·145	33·2	33·0
60	3·00	0·4800	1·170	1·188	33·6	33·3
70	3·60	0·5760	1·200	1·240	34·1	33·4
80	4·20	0·6720	1·234	1·296	34·9	34·0
90	4·90	0·7840	1·276	1·368	35·5	34·1
100	5·60	0·8960	1·321	1·443	36·4	34·5
120	7·97	1·275	1·473	1·727	36·8	33·5
140	10·8	1·728	1·655	2·102	38·5	32·4
160	15·0	2·400	1·945	2:698	40·7	33·8

The mean value of $R_{max.}$ is 33·3 kilovolts per centimetre. This compares with the value 33·4 found from Table 5.

TABLE 15.

Two equal spheres.

Radius $= a = 3{\cdot}125$ *cm.*

$$R_{max.} = \frac{E_1 - E_2}{x} f_1 - \frac{0{\cdot}86\ (E_1 - E_2)}{x} (f_1 - f).$$

$(E_1-E_2)\sqrt{2}$ Kilovolts	Spark-gap, x in cm.	$\frac{x}{a}$	f	f_1	$\frac{E_1-E_2}{x} f_1$	max.
10	0·42	0·1344	1·045	1·045	35·2	35·2
20	0·86	0·2752	1·092	1·094	36·0	35·9
30	1·35	0·4320	1·148	1·164	36·6	36·3
40	1·92	0·6144	1·214	1·262	37·2	36·3
50	2·55	0·8160	1·288	1·389	38·5	36·8
60	3·45	1·104	1·400	1·595	39·2	36·3
70	4·60	1·472	1·488	1·886	40·6	35·4
80	6·20	1·984	1·763	2·324	42·4	36·2

The mean value of $R_{max.}$ is 36·1 kilovolts per centimetre. This compares with the value 36·2 given by Table 4.

From the results given above we conclude that the spheres act as if their potentials were 0·57 $(E_1 - E_2)$ and $-0{\cdot}43\ (E_1 - E_2)$ respectively.

EXPLANATION OF THE POTENTIAL VALUES.

The author does not know the nature of the apparatus that was used for the test or how it was arranged. The simplest explanation he can suggest of the anomalous

results obtained when one electrode was earthed is the following. A transformer with a high-tension winding may have been employed. The centre of this winding may have been earthed. When the electrodes were insulated the electromotive forces generated in the halves of the transformer winding would have been equal and the electrodes would have been at equal and opposite potentials. If, however, one of the electrodes was earthed through a high resistance one half of the transformer winding would be loaded with this resistance and the other half would be practically on open circuit, as the capacity current is negligibly small. Let us suppose that the voltage drop on the loaded side was 25 per cent. Then it would always have this value whatever the voltage, whatever sized spheres were used as electrodes and whatever their distance apart. Hence if 57 kilovolts was the potential of the insulated electrode the potential of the other would be $-(57 - \frac{25}{100} \times 57)$, that is, -43 kilovolts. On this assumption, therefore, from what we have shown above it would follow that the maximum electric stress between the two electrodes determines in all cases the disruptive discharge.

The above explanation is only offered tentatively and possibly some other explanation is the correct one.

Unequal Spheres.

When the spherical electrodes are unequal the formulæ given in "Alternating Currents," vol. 1, chap. viii, enable the maximum stress at the surfaces of the two spheres to be computed. It is not easy to see which of them determines the disruptive voltage. As the potentials of the two spheres will not be equal and opposite the calculation of the maximum stresses will be laborious. It offers a promising field for experimental research as curious results will probably be found.

Tables.

The author has found the numerical calculations in this paper rather laborious. He would suggest that the time has now come when complete tables of the values of f and f_1 should be constructed. He would also suggest that Kelvin's tables of the electrostatic capacity coefficients between equal spheres and of the coefficients which enable their attractions to be found be expanded and completed. The labour involved would not be great and the tables would be at least as valuable and useful as many of those recently computed by the British Association.

Summary.

(1) Simplified formulæ are given by means of which the maximum electric stress between equal spherical electrodes can be readily found.

(2) Experimental results on sparking voltages when the potentials of the equal spherical electrodes are equal and opposite are analysed. It is found that if a be the length of the radius of each electrode in centimetres, the maximum potential gradient $R_{max.}$ at the instant of discharge is given by

$$R_{max.} = 27{\cdot}4 + \frac{14{\cdot}1}{\sqrt{a}} \text{ kilovolts per cm.}$$

very approximately when the temperature of the air is 25° C. and the height of the barometer is 76 cm.

(3) The sparking voltage E between two spherical electrodes, the radius of each being a, and x being the distance between them, is given by

$$E = \frac{x}{f}\left(27{\cdot}4 + \frac{14{\cdot}1}{\sqrt{a}}\right) \text{ kilovolts}$$

at 25° C. and 76 cm. pressure, where f is a factor which can be easily calculated from the geometrical dimensions.

It has to be remembered that these formulæ do not apply to air-gaps less than 1 mm. or air-gaps so great that brush discharges take place.

(4) It follows from the formulæ given above that in general for a fixed spark-gap there are certain sized spherical electrodes which offer the maximum resistance to sparking. Increasing or diminishing the size of the electrodes from this value makes the spark take place more readily.

(5) The results when one electrode is earthed given in the "Standardization Rules" of the American Institute are analysed. From the results it appears that the potentials of the electrodes were not E and 0, but were $0{\cdot}57\,E$ and $-0{\cdot}43\,E$. These values of the potentials make the values of $R_{max.}$ deduced the same as the values found when the potentials are equal and opposite.

DEVELOPMENTS IN ELECTRIC IRON AND STEEL FURNACES.

By J. Bibby.

(*Paper received 9 April, and read at a Joint Meeting of* The Institution *and* The Iron and Steel Institute, 8 *May*, 1919.)

The author proposes to confine his remarks in this paper to some of the recent developments in the manufacture of iron and steel by means of electric furnaces, as he imagines this will be more acceptable than to treat the whole subject generally.

Let us first consider the application of electricity to the reduction of iron ores, namely, to the manufacture of pig iron. Iron occurs in nature in the form of oxides, which can be reduced in contact with carbon at certain temperatures. In the electric furnace the function of electricity is to bring the ores and reducing agents to the temperature at which reduction takes place, and then melt the resulting metal together with the fluxes. Although there are technical advantages in electric heating over direct fuel-heating, the commercial success of the electrical reduction of iron ore depends on the price of electricity as compared with that of fuel. The profitable application of the electrical process is therefore limited to those districts where cheap electric power can be obtained.

The manufacture of pig iron in a blast furnace requires, on an average, one ton of coke per ton of pig iron produced. Given the same ore, an electric furnace would require 0·3 ton of coke per ton of pig iron produced, thus effecting a saving of 0·7 ton of coke per ton of iron. Against this saving in coke must be set the consumption of electrical energy, which averages 0·3 horse-power-year per ton of iron. This means that, other conditions being equal, the costs of the two systems balance when 1 horse-power-year can be obtained for the price of 2·3 tons of coke.

Electric pig iron contains less impurities than pig iron from the blast furnace, owing chiefly to the smaller quantity of coke used and to the higher temperature obtainable. The higher temperature makes it possible to work with a more basic slag, which favours the elimination of sulphur. There are now over 20 electric furnaces working on the manufacture of pig iron, and, at the moment, about 12 more are being installed, which is a good indication of the commercial hold the system is taking.

The general appearance of the electric reduction furnace (Fig. 1) follows that of the blast furnace fairly closely. The stock charging and hoisting gear are the same. The shaft is somewhat similar, except that it is only about 30 ft. high instead of 80 ft. At the point corresponding to the tuyere belt in the blast furnace the shaft proper of the electric furnace ends, and, in place of the narrow blast furnace hearth, there is provided in the electric furnace a wide shallow hearth or crucible, the shape of which is characteristic. This crucible forms the melting and refining chamber, and it is with the occurrences in this chamber that the electrical engineer is chiefly concerned.

In the blast furnace the necessary heat is generated in the tuyere zone by the combustion of the coke indirectly to CO. The hot combustion products ascend the shaft and reduce the ore in the zone in which a sufficiently high temperature obtains. The reduced iron, in the form of sponge, descends the shaft and is melted in the fusion zone round about the tuyeres, whence it trickles down to the hearth. In the electric furnace the necessary heat is generated by the resistance to the passage of current between the electrodes, which project through the roof of the crucible and are embedded in the charge.

At this stage we may consider the chemical action taking place in the electric furnace. The iron ore, coke, and flux are charged at the top of the furnace, and these, in descending, are heated by the ascending gases generated at the base of the shaft and top of the crucible by the final reduction which takes place in this region. When the temperature of the ore, Fe_3O_4, has reached about 250° C., it is reduced to a lower oxide, FeO, by part of the ascending CO, forming CO_2. The full reduction process can be set out as follows:

$$Fe_3O_4 + 3C + 3CO \longrightarrow 3FeO + 3C + CO_2 + 2CO \quad . \; . \; . \; (1)$$

$$3Fe + 3CO \longleftarrow 3FeO + 3C \quad . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

It will be seen that with every molecule of magnetite ore there should be three molecules of carbon, and this carbon descends, without change, till the temperature is sufficient for reaction. Equation (2) shows that the final yield is three molecules of iron which descend, two of CO and one of CO_2 which ascend; so, theoretically, there are 12 parts by weight of carbon charged to 56 of iron produced, that is 22 per cent, and it is satisfactory to find that, in the furnaces built recently, no more than this quantity of carbon is consumed per unit of iron produced. The first reduction to ferrous oxide by CO is at the temperature of 250° C. mentioned above, but the reduction of the ferrous oxide by solid carbon does not commence until a temperature above 800° C. is reached, so that reduction is not completed until part of the oxide is in the crucible.

It will be noticed from the equations that in the electric process the whole of the gas is produced from the oxygen in the ores and the carbon in the fuel, neglecting flux action, whereas in the blast furnace a large quantity of external air must be introduced to provide the balance of oxygen necessary for the combustion of the fuel for heating. In the electric furnace the gas generated is only one-eighth of that

generated in a blast furnace for the same duty, but its calorific value is nearly three times as high, inasmuch as it contains no nitrogen.

Besides the melting and final reduction operations in the crucible we have to melt the flux so as to form a slag with the gangue of the ore and the ash of the coke, and at the same time eliminate as much as possible the sulphur introduced by the ore and the coke. The sulphur is eliminated through the agency of the lime, forming calcium sulphide, which is retained in the slag. The slag should be highly basic in order that it may absorb the sulphur, which would otherwise remain in the iron as sulphide of iron. This necessitates a high temperature, owing to the high melting point of lime, but it would be futile to have a high temperature at one part of the metal-slag contact area and a low temperature at another, as in that case the sulphur

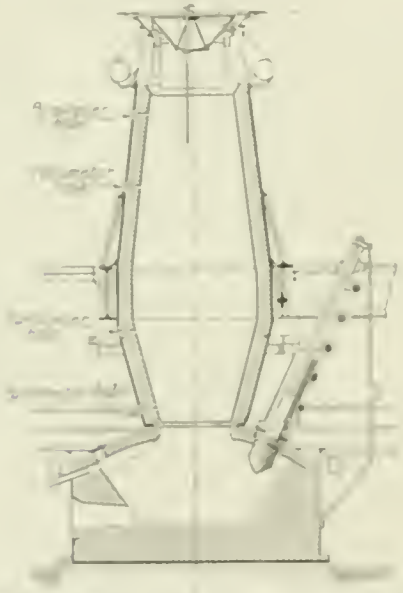


Fig. 1.—Electric Metals reduction furnace.

would pass back from the slag into the metal, at the cold places, and neutralize the good work at the hot places. The heating system must therefore be arranged so as to develop a uniformly high temperature throughout the central and lower portions of the crucible. We will now consider the means which are taken to accomplish this thermal state.

At before mentioned the heat is developed by the resistance of the loose charge to the passage of current between embedded electrodes. It is difficult to ascertain the voltage gradient throughout the charge, in the varying form in which it appears in the crucible, where it consists of ferrous oxide, melting iron, gangue, fluxes and small portions of coke. It appears, so far impossible to obtain as high a voltage drop across the crucible as we would like, and the drop does not increase quite in proportion to the distance, indicating, as would be expected, that there is a considerable drop between the electrode and the material which drop is constant for any given electrode and current. The effect is to have a higher rate of heat generation around the electrodes than in the intermediate spaces. However, it does not materially affect matters if we consider that the resistance between the electrodes is uniform throughout the space between them, i.e. that it is proportional to the distance.

It will be obvious that the larger the furnace the greater will be the number of electrodes required to distribute the heat sufficiently; and further, since up to the present no electrodes have been made having a greater capacity than 20,000 amperes, a number of electrodes are required to get the desired quantity of energy into the furnace. The main factor, however, is distribution. The following table gives the number of electrodes used on various sizes of furnaces and the outputs:—

Horse-power	Number of electrodes	Yearly output
2,500	4	7,000 tons
4,000	6	11,500
6,000	8	18,000
10,000	12	31,000

Commercially the smallest furnace is the 2,500 horse-power, with an output of 7,000 tons of pig per year.

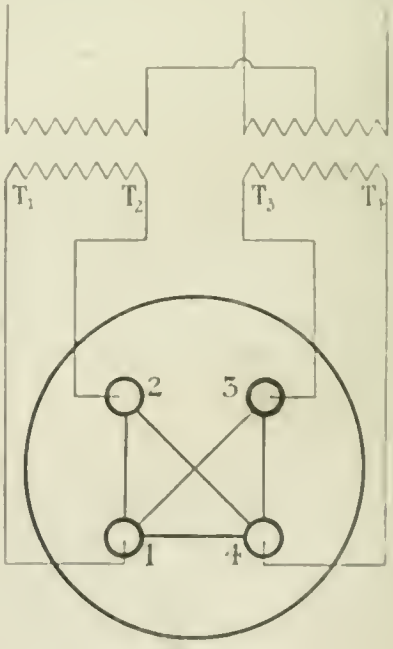


Fig. 2.

In this furnace we have four electrodes coupled to the secondary terminals of a Scott group; and the first scheme was to connect them as shown in Fig. 2, where the lower part of the diagram represents a horizontal

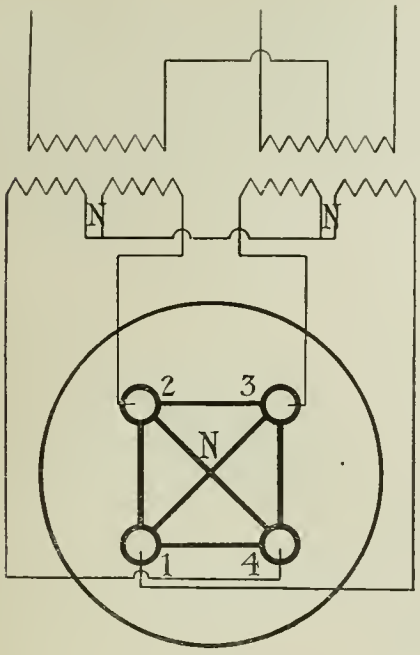


FIG. 3.

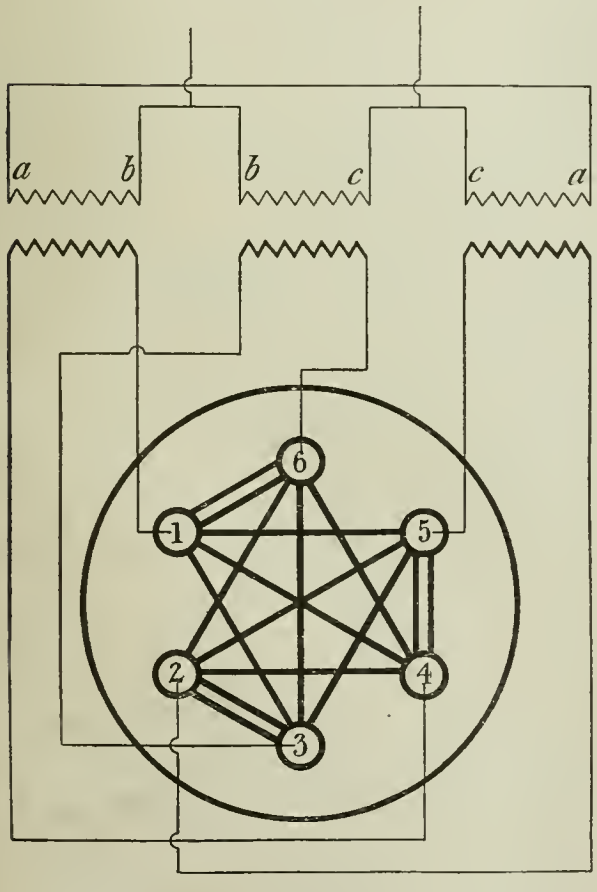


FIG. 4.

section through the crucible at the ends of the electrodes Nos. 1, 2, 3 and 4. The voltages across the electrodes 1–2 and 3–4 will be equal, but the voltages between the other pairs of electrodes need not be the same; for instance, there is no need for any voltage drop between electrodes 2 and 3, in which case there would be no current passing between these electrodes and no heat generated in the space between them. Similarly, the voltages between electrodes 1 and 4 may be 1·4 times the phase voltage, and in this case there would be an excess of current, and consequently excessive heating, between electrodes 1 and 4. The lines between the electrode circles represent roughly what may be con-

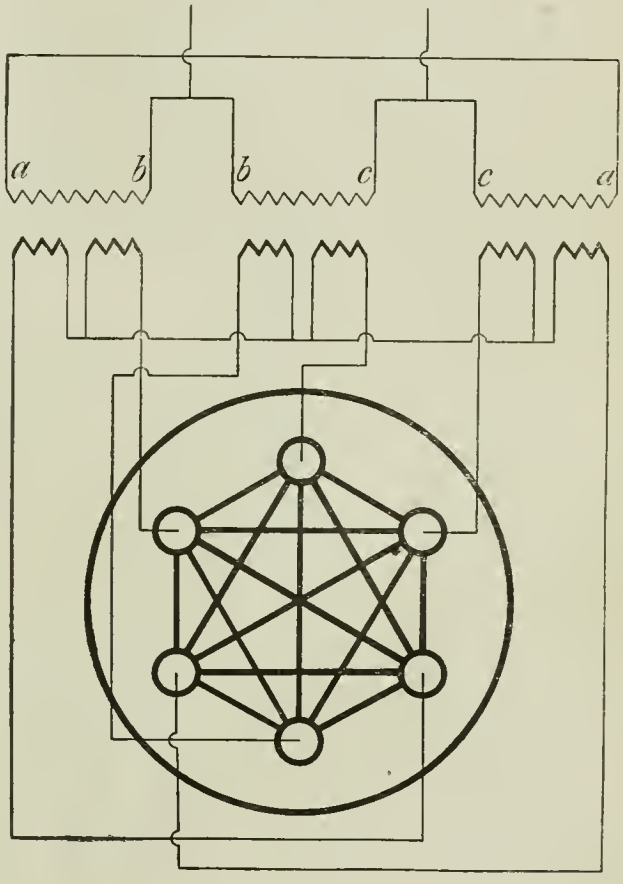


FIG. 5.

sidered to be the lines of heat generation in the crucible. The effect was to produce excessive heating at certain places, for example, between 1 and 4 electrodes, and deficient heating at other places, say between electrodes 2 and 3, resulting in irregular working and, what was of serious importance, undue destruction of the lining, especially of the roof near the overheated portions. This difficulty was overcome in a very simple manner as shown in Fig. 3, where the neutrals on the secondary side of the Scott group were connected so as to obtain the effect of four equal independent phases between each electrode and an imaginary neutral point. The potential between the electrodes and the neutral can

be represented by the semi-diagonals, and that between the electrodes, externally, is 1·4 times the voltage to the neutral. These voltages are proportional to the respective distances, so that the rate of heat generation along all the lines connecting every pair of electrodes will tend to be uniform.

The next size of furnace, viz. the 4,000 horse-power, requires six electrodes, and the idea on the early furnaces was to employ three single-phase transformers, between electrodes 1 and 2, and it was possible to have as high a voltage between adjacent electrodes 1 and 6 as between diametrically opposite electrodes. The result was a very irregular distribution of heat. There were zones of intense heat and zones where the heating was insufficient and, as a consequence, deficient working and local destruction of linings. The trouble was remedied, as in the four-electrode system, simply by connecting the neutrals on the secondary side so as

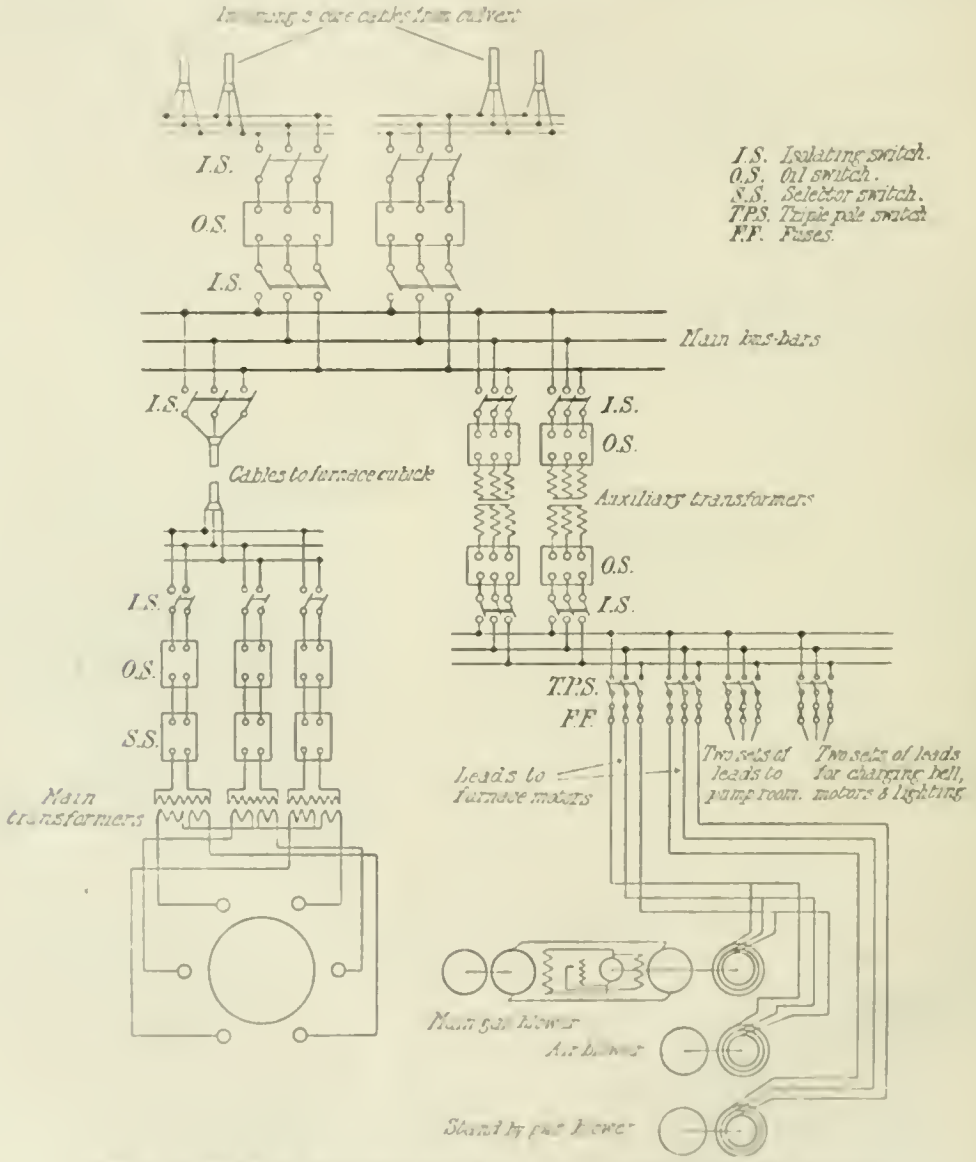


FIG. 6.—Diagram of connections for six 4,000 h.p. electric reduction furnaces.

delta-connected on the primaries, and the terminals of the secondaries connected to diametrically opposite electrodes as shown in Fig. 4. Although this arrangement secured equal voltages between diametrically opposite electrodes it by no means ensured regularity of voltages between the other pairs of electrodes; for example, there was no check for any voltage drop to secure the three phases being relatively fixed, and obtain the equivalent of six equal phases at 60°. The heating effect is approximately as shown by the lines in Fig. 5, and the improvement is obvious on comparing the two diagrams.

The next size of furnace, the 6,000 horse-power, has eight electrodes, and, for many reasons, it appears

that this is destined to be the most popular size. For this furnace we require to transform three-phase current into eight equal phases consecutively at 45°. There may be other ways of obtaining this transformation statically, but the plan which has been adopted is that which will now be explained. Five transformers, with relative ratios as marked, are connected on the

in N P and N M and represented in the diagram by O P and O M, giving the resultant E_1. Similarly, the voltages between the other electrodes and the neutrals are represented respectively by the equal vectors E_2, E_3, E_4, E_5, E_6, E_7, and E_8, at 45° progressively, which satisfies one condition of the system.

From the electric supply standpoint it is important

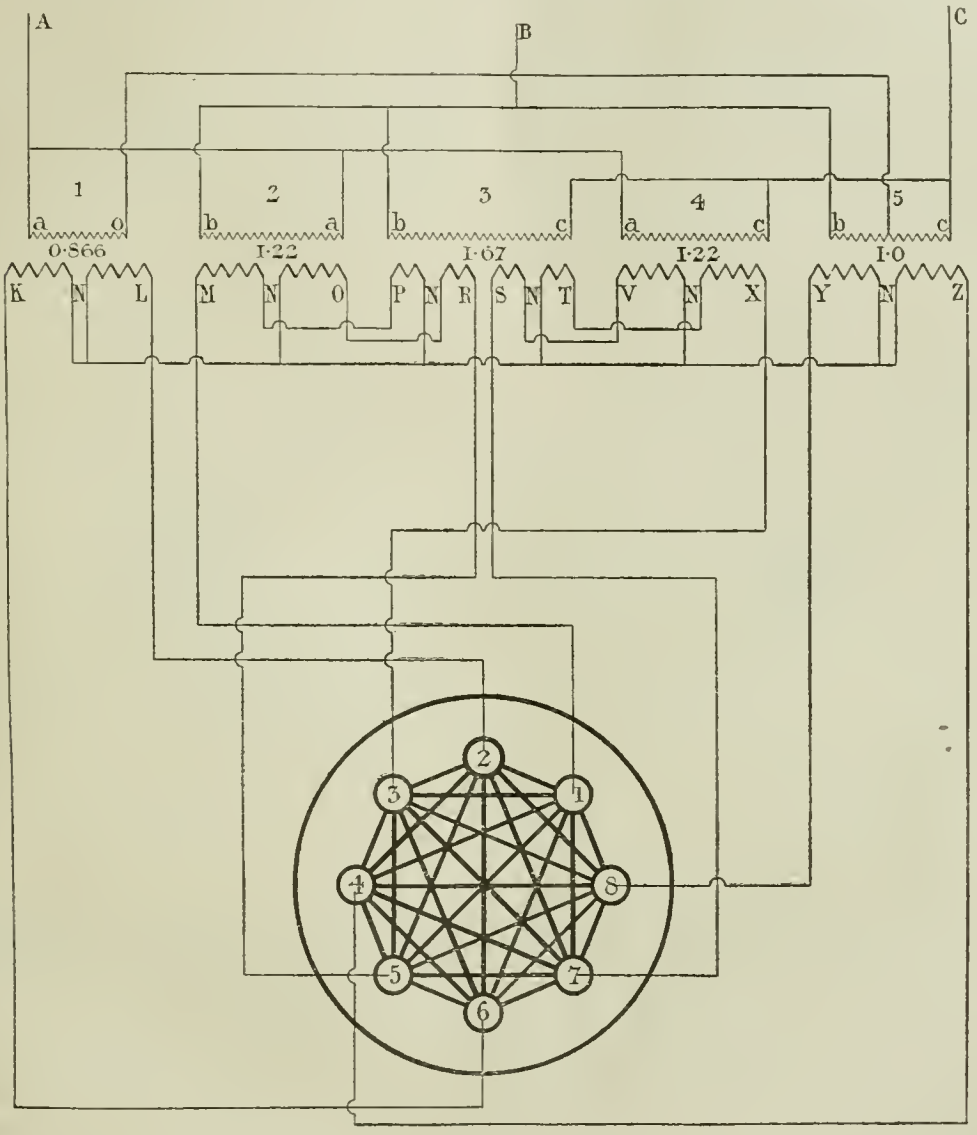


Fig 7.

primary side as indicated in Fig. 7, and the secondary terminals are connected to the electrodes in the order shown. The neutrals are connected for the same reason as on the smaller furnaces. When correctly proportioned, we obtain eight equal voltages induced between every electrode and the neutral. From the voltage vector diagram (Fig. 8) it will be seen that the voltage between No. 1 electrode and the neutral is equal to the vector sum of the voltages induced

that when equal currents are taken through all the electrodes, three equal currents should be taken from the primary mains. Fig. 9 is the current vector diagram, from which the current relationships can be followed, assuming that equal currents are taken through each electrode. The lines 1_c, 5_c, 3_c, and 4_c represent the currents induced in the primary C by the respective transformers. The vector sum of these currents is twice I_c. Similarly, the currents in the

other primaries are represented by twice I_a and I_b. This system satisfies the electrical condition for balance between the primary and secondary sides, and at the same time secures an exceptionally good heating distribution.

It will be observed that, if the electrodes are set out as shown in the diagram, the effective voltage between any pair of electrodes is proportional to the distance between their centres, and, consequently, if the resistance were constant, the amount of heat development could be represented by the lines drawn between the pairs of electrodes. As previously explained, this is not precisely what happens, since there is a constant voltage drop between the surface of the electrodes and the adjacent material.

The securing of a uniformly distributed high temperature gives the electric furnace an advantage over the blast furnace in this respect. In the blast furnace the

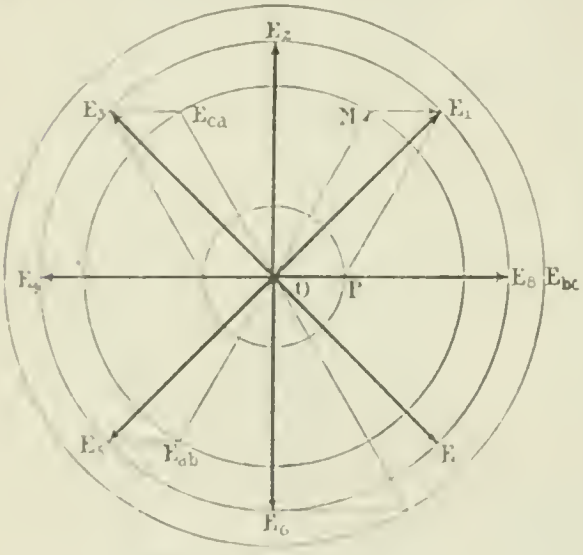


FIG. 8.—Voltage diagram.

temperature of the hearth is fixed by the possible temperature of the combustion at the tuyere zone, say 1,800° C., and this determines the melting point of the flux, that is, the possible proportion of lime. Now in the electric furnaces we have no such limiting temperature, and it is possible to have a flux with a melting point of 2,000° C., which permits of its being more highly basic and therefore more effective as a refining agent.

It might appear that the current passes horizontally between the electrodes, but this is not exactly what takes place in the crucible, as a portion of current is deflected through the molten metal on the hearth. Consequently, as the bath of metal rises, the resistance decreases, until a point is reached when it is impossible to get sufficient energy into the furnace, and the bath must then be tapped. This limit corresponds to that set by the height of the tuyeres in a blast furnace, but the growth of the bath is much slower, owing to its greatly superior width. An electric furnace is tapped every 4 or 5 hours, to suit the shifts.

The high temperature in the crucible would be destructive to the roof, even with regular heating, and to avoid this a portion of the outgoing gases is extracted from the main, taken through coolers and dust extractors, and blown against the roof through the free space between the charge and the roof. The gases are cooled to a temperature of about 70° C., and it is found that if about two-thirds of the gases are circulated the roof is effectively preserved. At the same time, this circulation assists in carrying the heat from the crucible into the shaft so as to effect the first reduction of the ore at a higher level. It will be observed that under this arrangement all the gas generated passes, on the average, three times through the shaft; but there is a distinct thermal loss by the amount of cooling necessary.

To ensure the proper working of the furnace under the inevitably varying conditions of the charge, it is

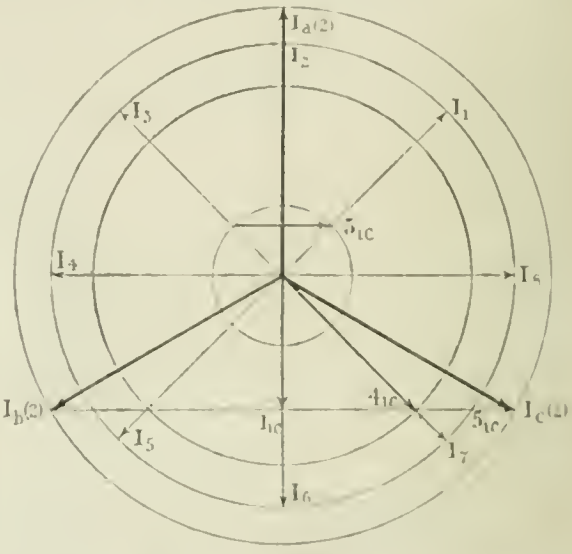


FIG. 9.—Current diagram.

necessary to have full control of the circulation gases and the electric energy delivered to the crucible. Regarding the energy supplied, it is not possible to have regulation of current, but the transformers are arranged with tappings on the primary side so as to give about eight steps of voltages on the secondary, varying from 25 to 50 between the electrodes and the neutral. The circulating gases are regulated by a direct-current motor-driven fan with wide speed regulation.

The general electrical scheme of a 4,000 horse-power six-electrode furnace is shown in Fig. 6, which is fairly self-explanatory. It will be observed that a motor-generator set is fitted for operating the fans. The single-phase transformers are of 1,200 k.v.a. each, shell type, water-cooled, with connected neutrals.

One of the most important points for consideration on the electrical side is the arrangement of the low-tension leads, each lead has to take a current of the order of 20,000 amperes, and therefore the greatest care must be taken to avoid induction. As an example of the losses which may occur in the low-tension leads,

it was found, in a test on an early furnace, that the output from the transformer was about 4,000 kw., but the input to the electrodes was 3,400 kw., showing a loss of 600 kw. The losses are distributed as follows :—

In the contact clamps at the electrodes ..	120 kw.
In the resistance of the leads	165 ,,
By induction	315 ,,
Total losses	600 kw.

The heavy induction losses were chiefly caused through the leads having to pass near the structural ironwork of the furnace. By re-arranging the leads and interleaving the bars the induction losses can be brought down to about 50 kw. On well-designed plants a power factor of 90 per cent is obtained, and a load factor of 80 per cent.

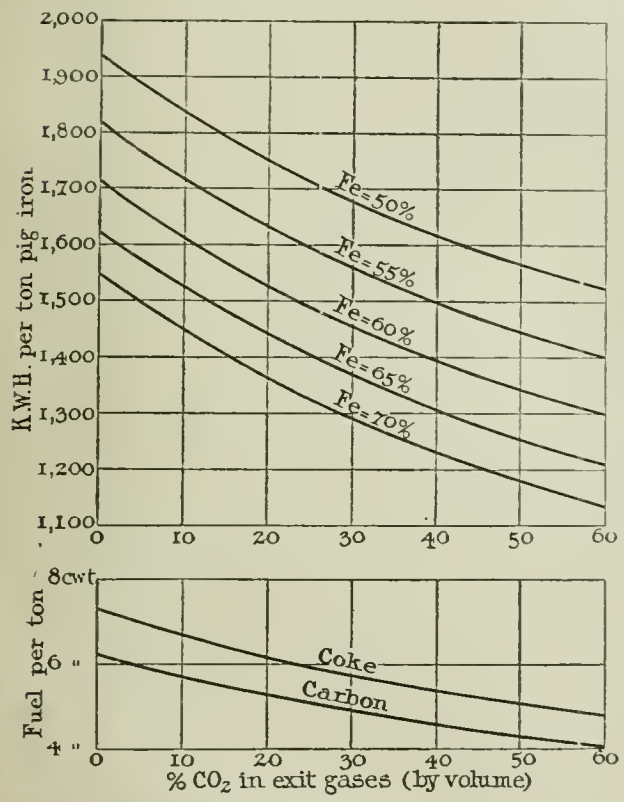


FIG. 10.—Fuel and energy consumption for electrical reduction of magnetite (Fe_3O_4).

The power consumption per ton of pig iron produced depends chiefly on the percentage of iron in the ore, on the percentage of CO_2 in the waste gas, and on its temperature. The ideal process would be to burn the whole of the carbon to CO_2, but the reducing value of the gas rapidly decreases as the percentage of CO_2 increases, until a point is reached when reduction ceases. In the electric furnace it has been found possible, under the best conditions, to approximate to the equation previously given where the final gas consists of $2CO+CO_2$, which gives 56 of CO to 44 of CO_2 by weight, that is, 44 per cent of CO_2, which is equal to about 33 per cent of CO_2 by volume. Fig. 10 shows the consumption of energy for various percentages of iron in the ore, and various percentages of CO_2, by volume, in the waste gases. In a good case of 33 per cent CO_2 and 70 per cent iron content, the consumption was only 1,320 kilowatt-hours per ton. The average obtainable, however, is 22 per cent of CO_2, and with, say, 60 per cent iron content the consumption is about 1,500 kilowatt-hours per ton. The consumption of fuel is given in the lower table, where the bottom line indicates the consumption of pure carbon, and the top line that of coke per ton of pig. It will be seen that for 22 per cent CO_2 the consumption of coke is only about 6 cwt. per ton of pig, excluding that required for carbonizing the iron, and this is a common figure in practice.

The working of the electric reduction furnace requires quite as much skill as the working of the blast furnace, but it is under better control and has greater possibilities for the production of various grades of iron.

Electric Steel Refining Furnaces.

The application of electricity to steel-refining has become much more general than to the manufacture of pig iron, inasmuch as in the former the price of electrical energy, although an important factor, is not the predominating one in determining the commercial value of a proposition.

In steel-making, electricity has advantages which place it well ahead of other heating systems. The chief of these advantages is that the heat can be supplied in easily regulatable quantities and intensities, free from contaminating gases. Moreover, the process can be carried on in a reducing atmosphere, which is of capital importance. Of the many methods of applying electricity that have been tried, the only one which has survived is the direct-arc type, in which the metal is heated by arcs struck between electrodes and the bath of metal itself. An incidental advantage of this system is that the slag is brought to a higher temperature than the metal, which is very desirable on account of its higher melting point, and, further, it is the most direct method of getting the heat into the metal.

In this part of the paper the author will deal with only some of the features connected with this particular system. Two types of furnaces have been developed on these lines, one in which all the electrodes are above the bath, and the other in which the electrodes are both above and below the metal. The first point to observe is that the resistance between any two upper electrodes is equal to the resistance of two arcs (the resistance of the metal being negligible), whereas the resistance between an upper electrode and a lower electrode is equal to one arc plus the resistance of the hearth. Now, in order that a number of phases may be in balance, it is necessary that the resistances in the phases be equal, e.g. if we have a three-phase furnace system we must have three equal resistances. In the Héroult three-phase system there are three upper electrodes connected to the outside terminals of three single-phase transformers. In this system the resistance between each pair of phases is equal to that of two

arcs, so that the arrangement gives a balanced system when correctly regulated.

If we have a three-phase system with two upper electrodes and one lower electrode, the resistance between the two upper electrodes will be equal to that of two arcs, and the resistance between either upper electrode and the lower electrode will be equal to that of one arc, plus the resistance of the hearth; so that, in order that the system may be balanced, the resistance of the hearth must be equal to that of one arc to bring the total resistance to two arcs, and this results in one-sixth of the energy being dissipated in the hearth. Now a basic hearth is a conductor of the second class, and the resistance decreases as a function of the rise in temperature. The resistance on the hearth surface in contact with the metal, where the temperature is about 1,800° C., is very small, but increases comparatively rapidly towards the bottom of the lining; so that the heat generated in the hearth, through its resistance, is principally towards the outside, away from the metal. The horizontal lines in Fig. 11 show the rate of heat generation throughout the depth of

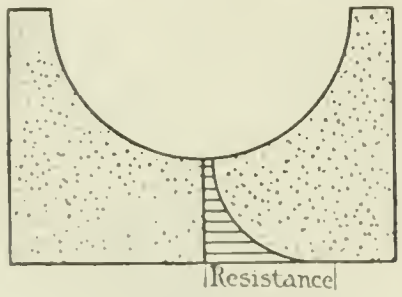


FIG. 11.

the lining. From this it will be seen that there can be no benefit to the metal through the generation of heat in the lining, but, on the contrary, it can be assumed that practically the whole of the heat thus generated is dissipated by radiation outside the furnace, rather than that any is absorbed by the metal. A three-phase furnace, or a furnace having any other number of phases so connected, and depending on hearth resistance for balance, although it might seem the simplest plan to adopt, is bound to be wasteful in current consumption. For any system to be balanced, without the introduction of resistances other than the arcs, the number of arcs must be a multiple of the number of phases.

[illegible] brings us to the determination of the number of arcs which should be used in an electric furnace. From a mechanical point of view the fewer the arcs the simpler the system; but the minimum number is determined by metallurgical considerations. There must be sufficient heating zones to melt the raw material rapidly, without necessitating undue exertion in pushing the unmelted metal towards the melting zones, and, by radiation, the temperature that the metal and slag should be brought to a high and uniform temperature. The reason for this relatively high temperature is that the basicity of the slag depends on its lime content, which fixes its melting point. The higher the content of the lime the higher the melting point, so that the higher the temperature the more possible it is to have a fluid, high basic, slag. The extent of the chemical action is indirectly limited by the minimum temperature of the slag, so that in order to get a uniformly high temperature, we must have no place in the furnace too far away from an arc, thus necessitating an adequate number of arcs to secure this condition.

Small furnaces have been made having a single arc, but it does not appear that any of these furnaces are in use for refining operations; they are simply employed for melting. There is the further difficulty of obtaining single-phase current from the usual three-phase supply without employing rotary transformers. It is found that two arcs sufficiently cover a bath up to about 6 tons' capacity, and there is no necessity to employ more that two upper electrodes for furnaces up to this size. In order to satisfy the conditions for balance, without the serious hearth resistance loss before mentioned, the two-arc system employed must only have two phases with a common neutral and as little hearth resistance as possible. Fortunately, a dolomite hearth is a fairly good conductor at the working temperature, and the loss through a depth of 12 inches, which is an ample thickness for a furnace hearth, involves a drop of only two or three volts at a current density of 3 amperes per square inch. The two-phase current is readily obtained from a three-phase supply by the usual plan of Scott-connecting two transformers, or by employing two phases of the four-phase system (to be described later) with two phases cut out and the transformer ratios modified to give two quadrature currents.

The main field for these small two-arc electric furnaces is in small foundries manufacturing better-quality castings, such as motor-car parts, etc. The castings made from the electric furnace are superior to those made from small converters, since the metal is thoroughly deoxidized and the sulphur content is reduced to a minimum. The predominating cause of defects in steel castings, apart from moulding errors, is the presence of oxides, and the freedom from oxides in electric furnace metal is a positive step forward; also, owing to the reduction in sulphur, the metal is much more ductile and uniform in composition, so that electric steel castings are freer from contraction tears and are much more easily machined. Waster castings, which figure so largely in ordinary steel foundry work, are reduced to an almost negligible quantity. These small electric furnaces are also rapidly displacing the ordinary crucible furnaces for the manufacture of higher quality steels such as ordinary tool, spring, tungsten, nickel-chrome steels, etc. The electric furnace is able to manufacture accurately to specification all kinds of steel from the cheapest raw material, since the reducing atmosphere permits of the alloy additions being made practically without loss.

There is an important use for the small furnace of about half-ton capacity, and that is the melting of ferro-manganese for use in conjunction with open hearth furnaces. When solid ferro-manganese is added to molten steel in the ladle, it is only reluctantly absorbed

and at least 30 per cent of the manganese content is lost by oxidation. Portions of the manganese are liable to remain unabsorbed by the steel, and these form manganese ghost lines in working, and hard places

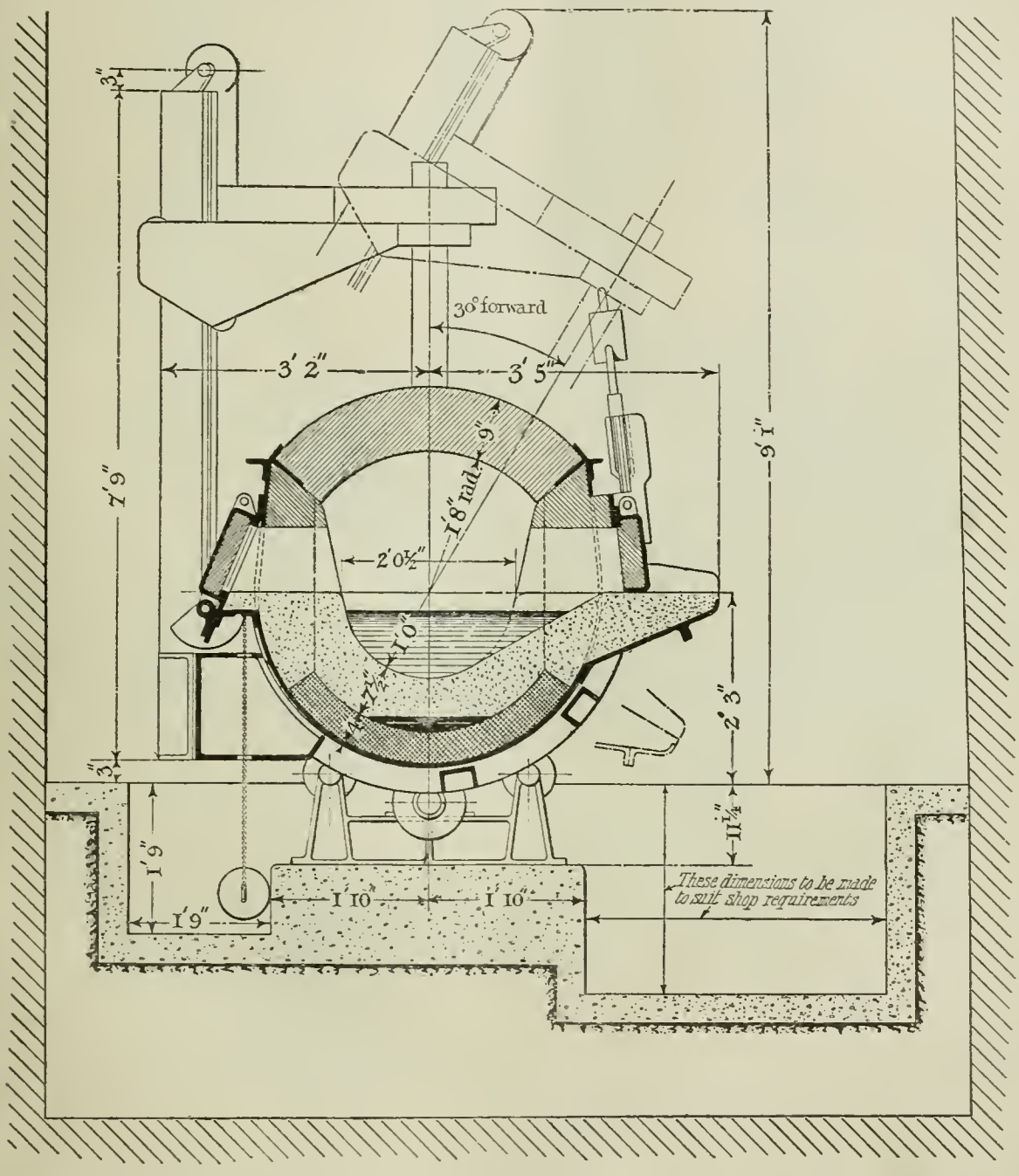


FIG. 12.—10-cwt. electric furnace.

which appear in machining. Ferro-manganese can be melted in the small furnace (Fig. 12) which has been specially designed for this purpose, and in which the manganese loss is not more than 5 per cent. There is therefore a great saving in manganese, which is an expensive metal; in fact the saving soon pays for the cost of the furnace, and the steel product is of higher value. These small furnaces have a capacity of 10 cwt. and will deliver molten ferro-manganese at the rate of 400 lb. per hour. The current consumption is 1,000 kilowatt-hours per ton of ferro-manganese delivered.

Although there are profitable fields for small furnaces, the principal technical developments will take place in larger furnaces. These furnaces may be used either

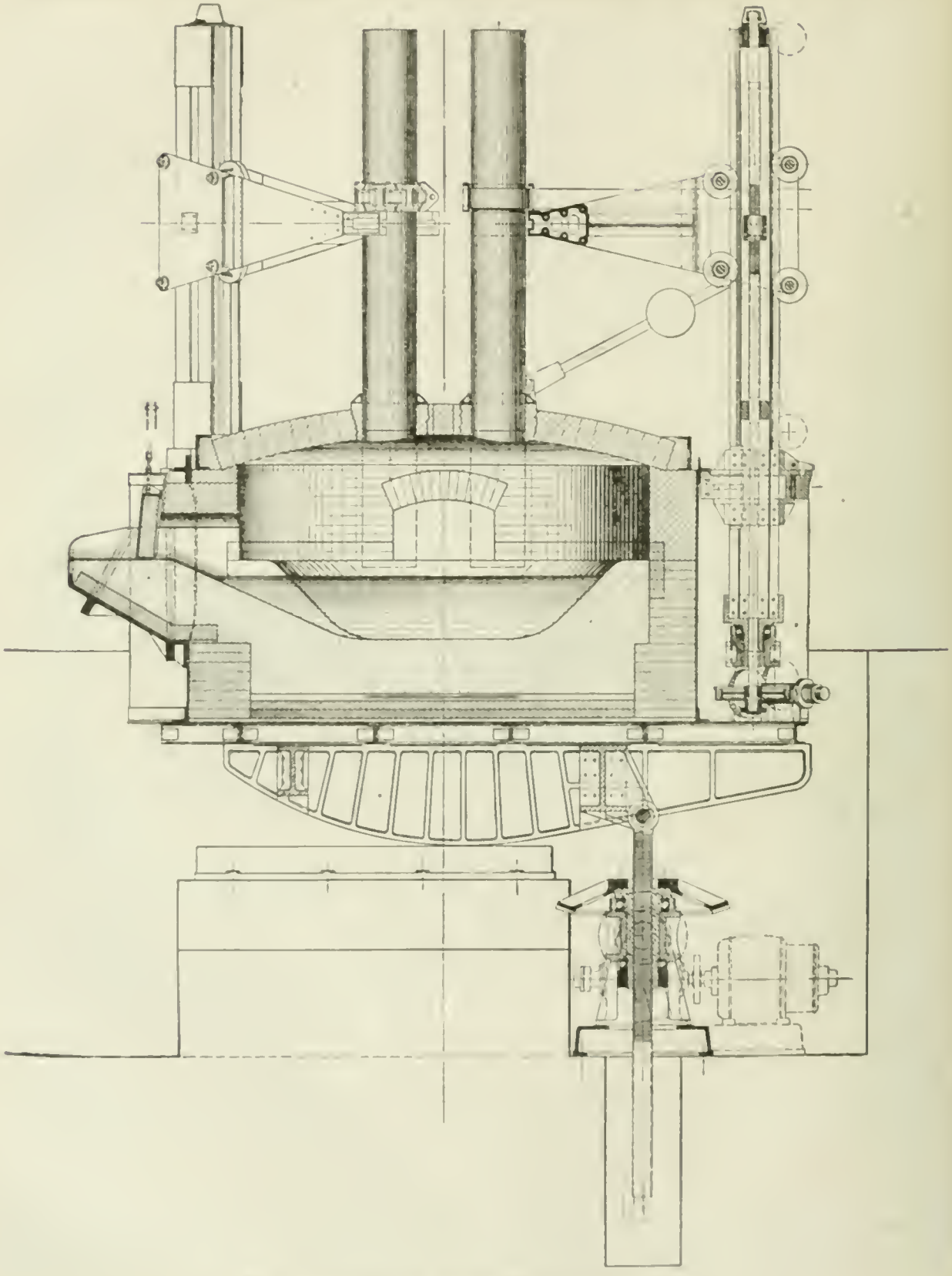


FIG. 13.—25 ton 4 phase steel refining furnace (elevation).

for the complete process of melting, refining and alloying, or may be run in conjunction with Bessemer or open-hearth furnaces, being used to refine the cruder metal from those furnaces. In this case, advantage is simply taken of a feature of the electric furnace, viz. that which permits of working under a non-oxidizing atmosphere at any desired temperature.

As previously mentioned, it is important that the heat supplied should be well distributed over the slag-metal contact area in order to ensure that the chemical reactions take place regularly as required. These larger furnaces, consequently, require a greater number of heating zones, that is, a greater number of arcs. The furnace which will now be described has four upper electrodes, which are sufficient for furnaces up to 30 tons' capacity, and two of this size are about to be started up on the Continent. This furnace is shown in elevation and plan in Figs. 13 and 14. The furnace is circular in plan, and the masts which support the electrode carriages are distributed round the furnace as shown. In the scheme of an electric furnace it is important to have as few openings as possible, and, at the same time, to have these so placed that every portion of the hearth can be surveyed and be accessible

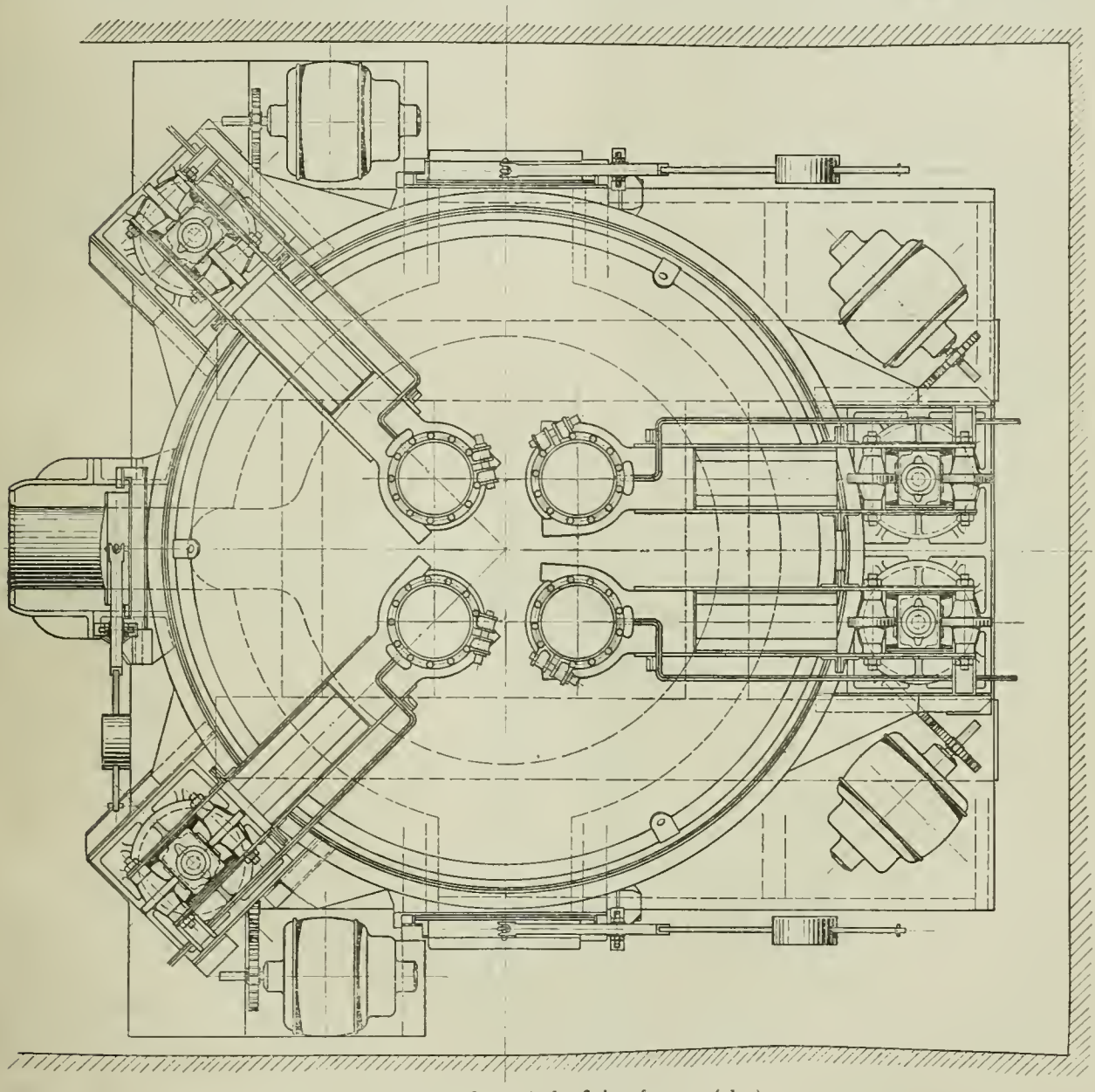


Fig. 14.—20-ton 4-phase steel-refining furnace (plan).

for any necessary lining repairs between the heats. Three doors are sufficient, one for teeming and two for charging, but this number is only sufficient if the doors are correctly placed and providing there are no obstructions to the men working at the doors. It will be seen that the disposition of the masts is such that all the mechanism is well clear of the doorways. The motors, which are the mechanisms nearest to the doors, are

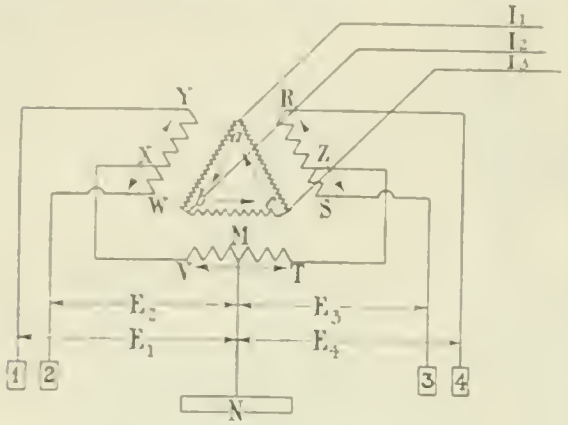


Fig. 15.

below the working platform. The doors must be designed to be always free to move and to form a good seal when closed.

The electric system on the large furnace requires, for the reasons given, four equal phases, preferably with only one variable resistance in each phase to facilitate definite regulation. We therefore require four phases with a common return through the hearth, so that the resistance in each phase is equal to the varying resistance of one arc plus the constant resistance of the hearth. The arrangement, as used for a three-phase supply, will now be described. The four-phase five-wire system must be so arranged that the current through the hearth will be a minimum, and this can be taken as the current in one phase, so that when starting the furnace one full arc can be struck independently of the other three upper electrodes.

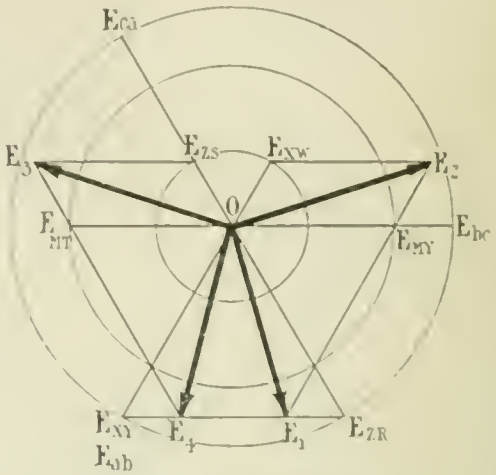


Fig. 16.—Voltage diagram.

The system consists of three single-phase transformers, arranged as in Fig. 15, with the primaries delta connected, and the secondaries in such a manner that, from the terminals of two transformers, Y, W, S, and R, connections are made to the upper electrodes

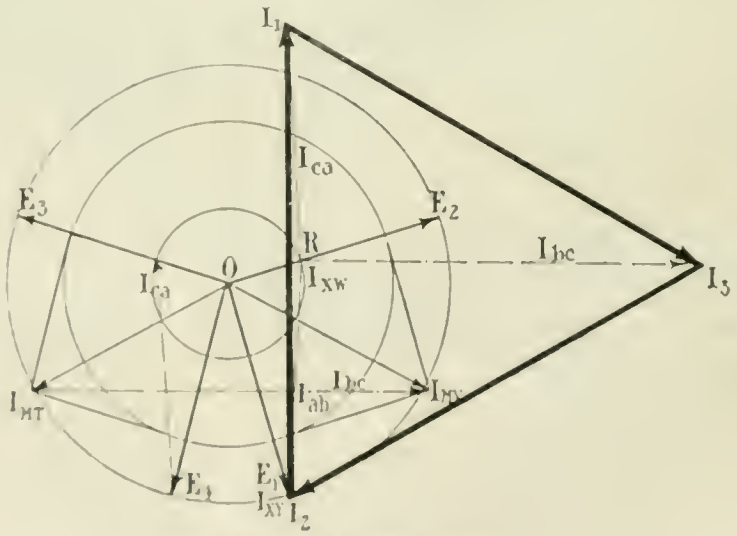


Fig. 17.—Current diagram.

1, 2, 3, and 4 respectively; and from the centre M of the third, or teaser secondary to the neutral electrode, N, beneath the hearth. From the terminals V and T of the teaser, connections are made to intermediate points X and Z respectively on the other two or main transformers. When arcs are struck beneath the

electrodes we have four practically independent circuits. The development of the system is shown clearly in the vector diagram. In Fig. 16 the three circles have radii corresponding to the transformation ratios of the sections of the secondaries to the corresponding primaries. If we consider the three primary windings to be equal, then the radius of the inner circle can represent the number of turns in the sections X W and Z S, the intermediate circle the turns in M V and M T, and the outer circle the turns in X Y and Z R. The vectors E_{ab}, E_{bc}, and E_{ca} represent the directions of the voltages across the respective primary windings. The voltage induced between No. 1 electrode and the neutral is equal to the vector sum of the voltages induced in M V and X Y; so that if we mark off along the directions E_{bc} and E_{ab}, distances E_{MV} and E_{XY} corresponding to the turns in M V and X Y, the resultant E_1 will represent the voltage in the No. 1 electrode phase.

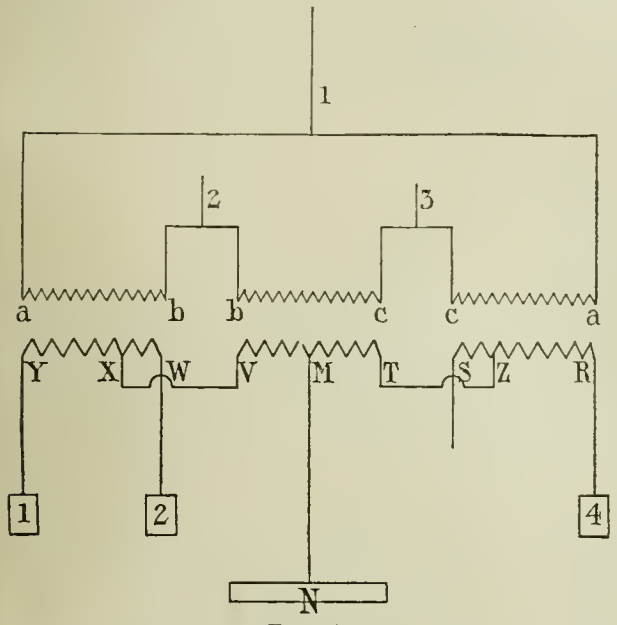


Fig. 18.

Similarly, the voltages in the other phases are represented by the vectors E_2, E_3, and E_4. It is a simple matter to proportion the windings so that these voltages are all equal, but it is necessary when equal currents are taken through each of the electrodes, as is the case in normal working, that three equal currents be taken from the primary mains. That this is so will be seen from the current diagram (Fig. 17).

Neglecting induction, the currents in the electrodes can be assumed to be in the direction of the respective voltages, so that we redraw the voltage vectors obtained in the previous diagram and assume equal currents in the electrodes. The winding W Y is under the influence of the currents in Nos. 1 and 2 electrodes. No. 1 electrode influences XY turns, and No. 2 electrode influences X W turns, so that if we mark off, along their respective directions, distances corresponding to the turns, for example, I_{XY} and I_{XW}, and then take the vector difference, I_{ab}, this will represent the ampere-turns in W Y, and therefore in the primary $a\,b$. Similarly, the ampere-turns in $c\,a$ are represented by the line I_{ac}. Concerning the winding T V, the current in M V is equal to the vector sum of the currents in electrodes Nos. 1 and 2, and the current in M T is equal to the sum of the currents in Nos. 3 and 4, so that if we mark

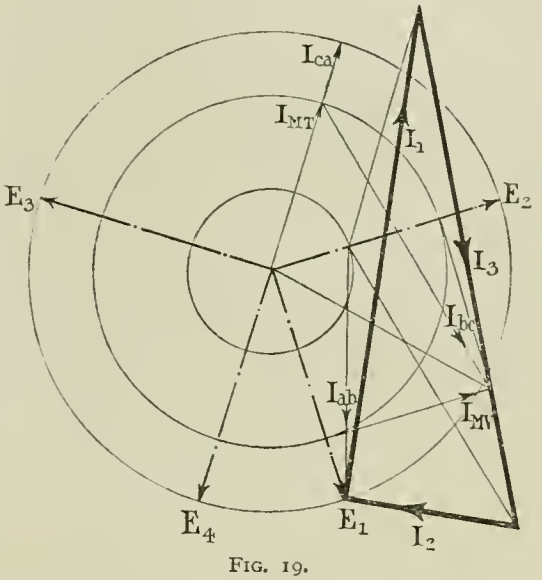


Fig. 19.

off along E_1 and E_2 the intermediate circle distance, that is the turns in M V, and then take the resultant I_{MV}, this will represent the ampere-turns in M V. Similarly, I_{MT} represents the ampere-turns in M T, and the vector difference I_{bc} is the ampere-turns across T V, and therefore in the primary $b\,c$. As we assumed

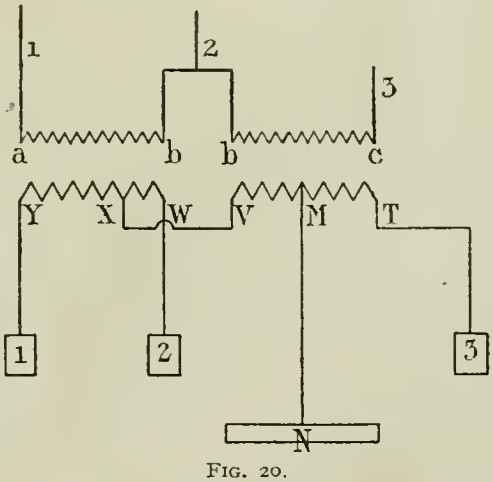


Fig. 20.

the primary turns to be equal, the lines I_{ab}, I_{bc}, and I_{ca} will represent the currents in the primary windings, and the sides of the equilateral triangle constructed thereon, I_1, I_2 and I_3, are the currents in the primary wires. The system is therefore balanced for current and pressure under normal conditions of correct regulation.

An electric furnace is, however, inevitably and frequently subjected to abnormal conditions, and it is of importance to know what is happening to the current in the mains when the furnace is working under the worst conditions. As far as the electrodes are concerned, the worst condition is when one arc breaks, as is so

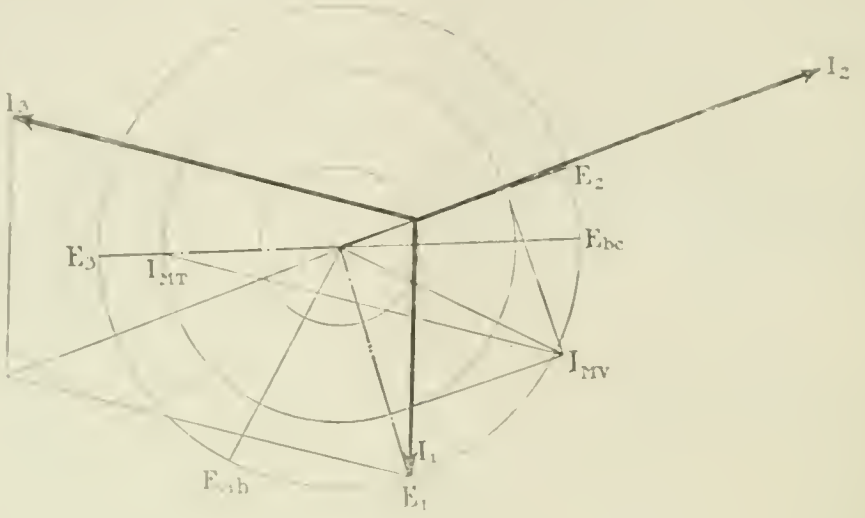


FIG. 21.

often the case. We will therefore assume, for example, that No. 3 phase is broken as in Fig. 18. In the vector diagram, Fig. 19 we have the directions of the currents in the three remaining electrodes, as before, and we will assume that the three currents in these electrodes are equal. The winding W Y is, as before, governed by the currents in Nos. 1 and 2 electrodes, and the ampere-turns across W Y are represented by I_{ab}. The winding S R has only the current of No. 4 electrode and its ampere-turns are therefore represented by I_{da}. For the teaser winding we have, as before, I_{MV} and I_{MT}, the difference I_{bc} will represent the ampere-turns in *b c*, so that we have the currents in the three primary lines represented by the sides of the triangle I_1, I_2, and I_3. The primary system is not balanced under this condition, but it is quite tolerable. Another extreme case is when one of the transformers has, for some reason, to be disconnected, as shown in Fig. 20. The currents in the primaries under this condition are represented by the three vectors I_1, I_2, and I_3 in Fig. 21, and it will be allowed that this is satisfactory.

It has been previously mentioned that practically all energy dissipated in the hearth is so much loss, and it is therefore important not only to reduce the voltage drop to a minimum, but also the neutral current. If we take this four-phase system, the current through the hearth is the vector sum of the currents in four electrodes, and this is approximately equal to that in one of them. This means that the volume of current through the hearth is, say, one-quarter the arithmetical sum of that in the whole of the electrodes. In the small two-arc furnace the current density is about 3 amperes per square inch, but on the four-phase furnace it is only 1 ampere per square inch, so that the drop in voltage is less than 1 volt, and the loss of energy in the hearth with this system does not exceed 0·3 per cent, and we have an arrangement which gives four independent phases, permitting of good electrode regulation. Careful tests have been made on a trans-former group connected up on this system, as shown in Fig. 22. The electrodes were regulated so as to give as nearly as possible the same current, and then spot readings were taken on the ammeters on the primary side. The figures given in the diagram are percentages of the normal, and it will be noticed that the variations from the normal are less than 1 per

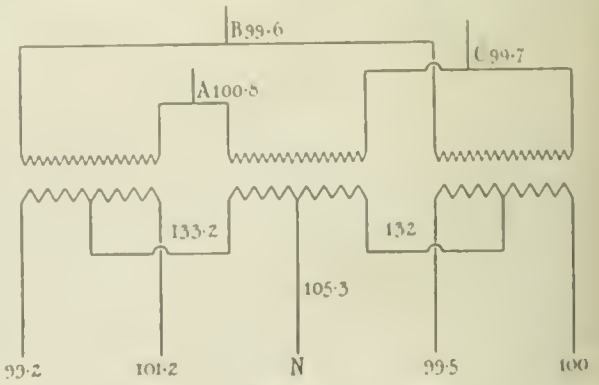


FIG. 22.

cent, and the current in the neutral is 5 per cent greater than that in the electrodes.

An interesting point in connection with arc furnaces is now the subject of an investigation, viz. the nature of an arc load. As is well known, the resistance of an arc decreases with an increase in current, so that with an alternating impressed voltage the specific resistance is at a minimum at the crest of the wave and at a

maximum at the zero line. The resistance curve, therefore, has a full pulsation for each half wave of the fundamental current, and is at a maximum at 90° from the maximum of the fundamental. This can be represented as follows :—

If R is the resistance for the R.M.S. value of the current, and K the factor connecting the amplitudes of the two curves, then

$$r = R\{1 + K \sin(90 - 2\omega t)\}$$
$$= R(1 + K \cos 2\omega t)$$
$$i = \frac{e}{r} = \frac{E \sin \omega t}{R(1 + K \cos 2\omega t)}$$
$$= \frac{E}{2R(1-K)}[(2-K)\sin \omega t - K \sin 3\omega t].$$

Both second and third harmonics occur, but if we develop the third, for example, in a Scott-connected group, we find that the harmonics are out of phase with two of the fundamentals, which is due to the fact that in such a group two of the third harmonics are the resultants of two third harmonics displaced by three right angles, which brings one resultant third harmonic

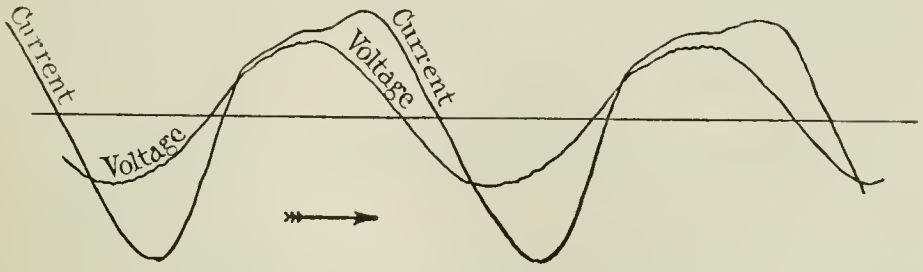


Fig. 23.

120° out of phase with the fundamental. In the development of any transformer system for arc loads, the effect of the third harmonic must be taken into account, as it is necessary that the third harmonics in the primary should be as nearly as possible in phase with the fundamentals at the maximum, so that the curves will not be too unsymmetrical. In the four-phase system we have third harmonics in the four secondaries, and it is a simple matter to develop the harmonics back on to the primary lines and see that they are almost in phase with the primary fundamentals. The distortion of the primary voltage waves is negligible. Dr. Chapman has analysed one of these current waves on a Scott group (Fig. 22) and finds it can be represented by the following equation :—

$$i = 2{\cdot}34 \sin\theta + 0{\cdot}202 \sin 2\theta + 0{\cdot}168 \sin 3\theta + 0{\cdot}566 \cos\theta - 0{\cdot}43 \cos 2\theta - 0{\cdot}17 \cos 3\theta.$$

This oscillogram shows the voltage-current relationship, and indicates a power factor of about 0·8. The small 27th harmonics on the voltage curve are from the transformer.

Among the first considerations in any proposal for installing electric furnaces are the available electric power and the price at which it can be obtained. Fig. 24 shows the capacities of transformers which must be supplied for given sizes of furnaces. It will be noticed that the capacity of the transformer required per ton decreases as the size of the furnace increases. This is because the radiation losses are proportionally greater in the smaller furnaces. Also, as is indicated on the same diagram, the consumption of current per ton decreases as the size of furnace increases. On a well-designed furnace the power factor is in the neighbourhood of 0·8, but it is necessary to have a large reactance, say 10 per cent or 12 per cent, in the system to choke the unavoidable fluctuations of current in the arc. From the electrical standpoint the most severe trial to which the plant can be put is when it is required to melt rough cold scrap, and when working on this duty momentary overloads of from 50 per cent to 70 per cent may occur, so that the transformers must be designed for such an emergency. The load factor on a single furnace working night and day is about 35 per cent, but when working two furnaces it is 50 per cent, which compares favourably with other loads on electric generating stations. It is unlikely that there will be much decrease in the consumption of current in the steel furnace of the future, since the thermal efficiency of a modern plant is about 65 per cent. Improvements will rather tend toward mechanical reliability and more durable refractories, especially for the roof. The metal will be melted in large plants by Bessemer or open-hearth processes and then charged into electric furnaces for refining and alloying. The electric furnace is not a cheap melter, its value being in its refining properties. When hot crude metal is charged into the electric furnace the energy and time required for refining is about one-third of that required for melting and refining, so that a furnace charged with hot metal has three times the capacity of one charged with cold stock.

With respect to refractories, the electric furnace is practically always lined with a basic hearth, which shows it up to great advantage in desulphurizing. The hearth is built in exactly the same way as in an ordinary open-hearth furnace, so there is no need to deal with it here. The average life of the roof is 100 heats, melting and refining, or about 400 working hours. During the war, when the cost of refractories was abnormally high, it was found that the average total refractories, including periodic relining, amounted to less than 8s. per ton of metal melted and refined.

Electrodes.

One of the most important items in the cost of running an electric furnace is that of electrodes, not only because of their initial cost but also because of the time lost in renewing them. In the reduction furnace the electrodes are embedded in the loose material. They are not regulated as in the steel furnace, but are simply pushed down every two or three days as they burn away. Now on a 4,000-h.p. furnace, with electrodes 28 inches in diameter embedded, say, 6 inches, the area exposed to the material is about 1,000 square inches. When passing 20,000 amperes the drop between an electrode and the material is about 20 volts, that is, the contact resistance is equal to 0·001 ohm. Since, in the reduction furnace, it is desirable to have as great a voltage drop between the electrodes as possible, in order to get sufficient energy into the furnace, and as the distance between them cannot be increased conveniently, the only way to increase the voltage is to increase the drop between the electrode and the material—and to do this we must decrease the contact surface, that is, the size of the electrode. In the reduction furnace we are therefore confronted with the problem of requiring an electrode which has a greater conductivity than the carbon electrodes now being used so as to reduce the contact surface. With carbon electrodes when working at 40 amperes per square inch on the large 28-inch size, we have a voltage drop at each electrode of 20 volts, and about 40 volts in the resistance of the intermediate material, giving a total drop of 80 volts. If we had an electrode which would work at 120 amperes per square inch, the diameters would only be about 16 inches, and the contact area about 300 square inches, so that the electrode contact drop would be 20 volts, giving a total drop between the electrodes of 120 volts. This would mean that, for the same size of electrodes and the same current, there would be 50 per cent more energy delivered to the furnace. Graphite electrodes will work at a density of 120 amperes per square inch, but, unfortunately, they have not been made, up to the present, more than 12 inches in diameter. Electric reduction furnace builders are therefore waiting for the graphite electrode manufacturers to turn out much larger electrodes.

The skin effect on the large carbon electrodes is detrimental, and this would be reduced with the smaller graphites. Also, graphite electrodes will allow of smaller holes in the roof. On the other hand, it must be taken into account that the thermal conductivity of graphite is five or six times that of amorphous carbon, whereas it has only three times the electric conductivity, so that the drainage of heat from the furnace by graphite is twice that by carbon for the same current-carrying capacity. In steel furnaces, where the resistance is simply the single arc, the surface is of no importance; the determining factor is the cost of electrodes per ton of steel.

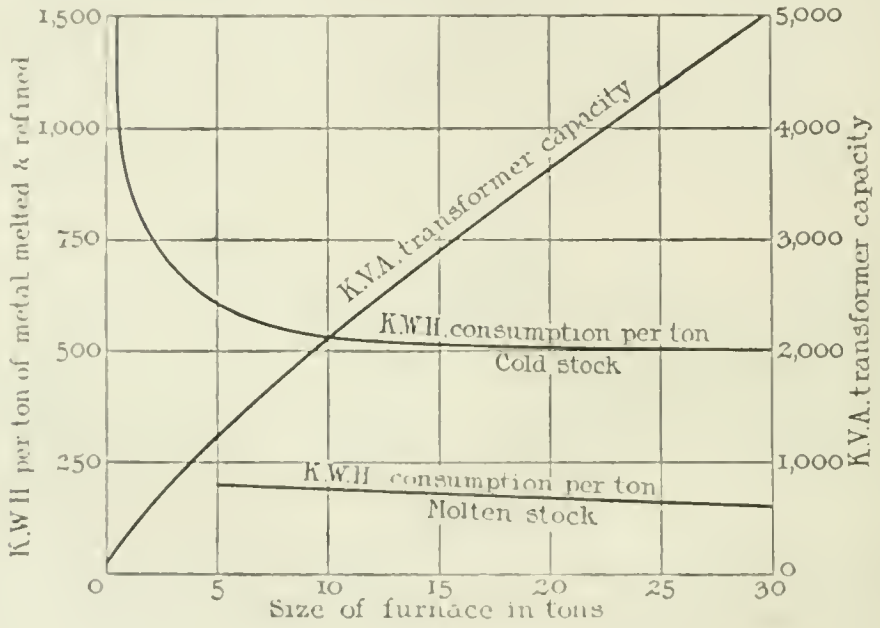


Fig. 24

Conclusion.

It will be seen that both the electric reduction furnace and the steel-refining furnace present interesting problems for electrical engineers, and that a fair amount of success has attended their efforts to solve these problems. Experience has shown how important it is that engineers should fully grasp the requirements of the metallurgists, and be fully acquainted with the working conditions of blast furnaces and of steel foundries.

[The discussion on this paper will be found on page 276.]

THE BOOTH-HALL ELECTRIC FURNACE.

By W. K. Booth.

(*Paper received* 23 *September*, 1918, *and read at a Joint Meeting of* The Institution *and* The Iron and Steel Institute, 8 *May*, 1919.)

The principal difference between the various makes of electric furnaces is the method in which the power is introduced into the furnace. The general metallurgical operations of practically all electric arc furnaces are the same. The method of power regulation and bringing the power to the furnace frequently means greater or less cost in furnace operation and governs, to a considerable extent, the manner in which the furnace lining may be put in and consequently the refractory cost and the loss of time due to furnace shut-downs.

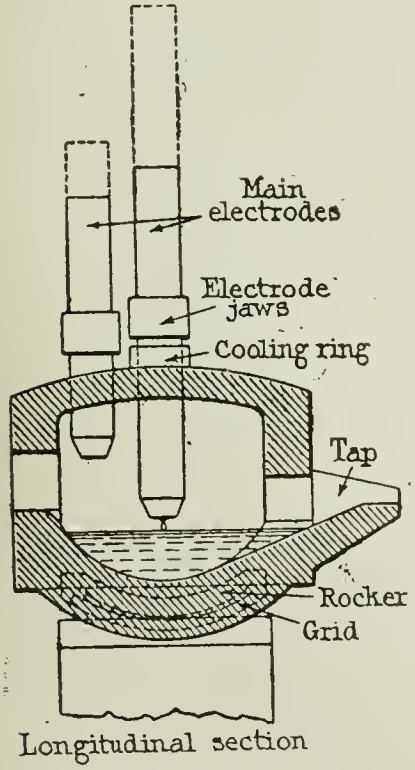


Fig. 1.—Booth-Hall two-phase furnace.

Electric arc furnaces may be broadly divided into two classes:—

(1) Vertical arc furnaces,
  (*a*) conducting hearth,
  (*b*) non-conducting hearth;
(2) Horizontal arc furnaces.

It is not the purpose, here, to enter into a discussion of the merits of the various types of arc furnaces, but more particularly to describe a new type of electric furnace which has been developed during the last year and which is known as the Booth-Hall electric furnace.

The Booth-Hall electric furnace comes under class 1 (*a*) above, and is illustrated diagrammatically in Figs. 1 to 4.

Fig. 1 is a longitudinal section of the two-phase electric furnace with the auxiliary electrode resting upon the charge and arcs drawn between the main electrodes and the charge. A pool of metal is shown forming on the hearth of the furnace.

Fig. 2 is a diagram of a transverse section of the two-phase electric furnace, showing the crossing action of the current in the bath and the grids embedded in the hearth.

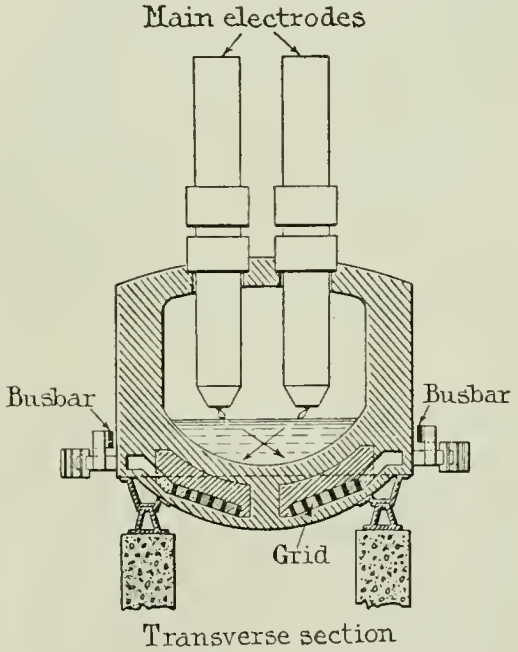


Fig. 2.—Booth-Hall two-phase furnace.

Fig. 3 is a diagrammatic representation of the electrical connections for the two-phase electric furnace employing two single-phase Scott-connected transformers. This diagram shows the connections from the transformer terminals to the main electrodes and to the auxiliary electrode and grids. A two-phase electric furnace so connected gives a balanced load on a three-phase power service. The auxiliary electrode is shown in black.

Fig. 4 shows diagrammatically the arrangement of main and auxiliary electrodes in single-, two-, and three-

phase Booth-Hall furnaces. The auxiliary electrodes are shown in black.

The furnace is built either single-, two-, or three-phase to suit the conditions at the place of installation, the general principle being a furnace having a solid hearth which becomes conductive of electricity when hot and the use of an auxiliary electrode which acts as a return for the electric current until the hearth becomes heated and conductive.

In starting furnace operation on a cold charge the auxiliary electrode is lowered until it rests on top of the charge and the arc is then drawn between the charge and the main electrodes or electrode, as the case may be, the auxiliary acting as a return for the main electrode or electrodes. The auxiliary is so arranged that it presses with its entire weight on top of the charge and consequently no arc can form underneath the auxiliary, and experience has demonstrated that no arc does form. The auxiliary is connected in parallel with the conducting hearth, and when the main electrodes or electrode have melted enough metal

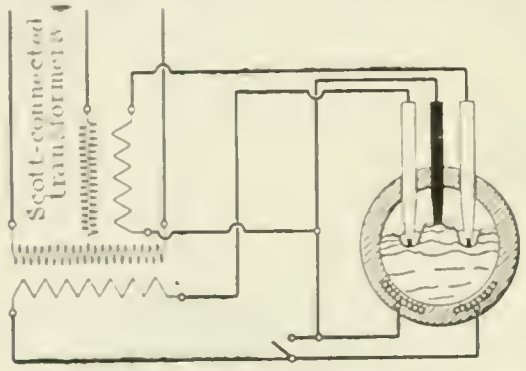


FIG. 3.—Electrical connections of Booth-Hall two-phase furnace.

to form a pool on the bottom the hearth becomes conductive and the auxiliary is withdrawn from contact with the charge. In a cold furnace the auxiliary is in operation from 30 to 45 minutes, and, in a furnace which is hot, less than 15 minutes, that is, only long enough to assure a positive start of the furnace and a balanced load on the power company's line.

Furnaces from ½ ton to 6 tons' holding capacity are generally built for two-phase operation, taking power from three-phase service by means of Scott-connected transformers, as shown diagrammatically in Fig. 3. In the hearth of the Booth-Hall two-phase electric furnace two sets of grids are embedded, which are electrically insulated from each other and are so related to the main electrodes that the current of the two phases cross in the bath, thus giving a maximum of circulation of the molten metal and causing, in conjunction with the effect of the bottom heating, a very thorough mixing of the metal in the bath. This action can readily be observed on looking into the furnace after the charge has entirely melted. The conducting grids are placed as far as possible from the heated interior of the furnace and experience has shown that they never become overheated or require special cooling. The grids are so constructed as to handle large currents, furnishing large areas of contact with the material of the conducting bottom, and preventing local heating due to contact resistance.

By the use of the auxiliary electrode a positive start of the furnace is guaranteed, and there is no possibility of failure to secure contact. Each main electrode is independent of the other, as there are no arcs in series, and consequently the regulation of the furnace is very simple, giving a balanced polyphase load on the power service lines. As with the two-phase connection there are only two electrodes to regulate, thus offers the minimum number of electrodes for a balanced polyphase load, and the smaller the number of electrodes requiring regulation the smoother becomes the furnace operation.

FIG. 4.—Diagrammatic representation of electrode arrangement.

The hearth is either acid or basic, as desired, and in each case is at least 24 inches (60 cm.) in thickness, being sintered in place layer by layer and forming a monolithic mass. By using the main electrodes in conjunction with the auxiliary, the materials of the hearth are sintered together in thin layers similar to open-hearth practice, thus forming a very durable bottom and making the danger of run-outs a minimum. The furnace hearth is consequently solid, with no water cooling of any kind. With the basic hearth, dead burned dolomite is used to maintain the slag line; in the acid furnace, ground ganister is used for the same purpose. The conducting hearth gives a uniform bottom heating of the entire bath, prevents sculls, and makes speedier and more thorough distribution of the heavier alloys, which tend to sink to the bottom of the bath. The effect of this bottom heating is considerable, and has been accurately measured on Booth-Hall furnaces in continuous operation.

With the two-phase electric furnace a minimum of electrode consumption is secured, due to the fact that a minimum number of electrodes for a balanced polyphase load is used. This means fewer electrodes to handle, less electrode breakage, and less surface burning. The loss on the auxiliary electrode is small, because it is

in operation for such a comparatively short time. The electrode jaws are made so that the electrodes can be gripped or released by turning a handwheel or lever at the side of the furnace, and it is not therefore necessary for the melter to climb on top of his furnace when changing the grip on the electrodes. The electrode jaws are arranged in segments so as to take up and adjust themselves to the inaccuracies in the surface of the electrodes.

A roomy charging door of special construction is provided in the rear of the furnace, and another door in front over the tap. This construction is very similar to the open hearth, and permits a battery of furnaces to be arranged side by side and a charging machine to serve them all. The furnace tilts or rocks backward as well as forward, and slagging operations can be handled from either the rear or the front as desired. The door is shown in the photographs exhibited. It is designed so that it comes flush against the door frame, sealing the opening, and cannot swing open of its own accord. This prevents air getting into the furnace and also prevents excessive losses of heat through the door. The door can be opened anywhere from a few inches to full open when inspecting the bath, taking tests, or pushing scrap from the sides of the furnace into the bath, thus protecting the melter from the heat of the furnace and preventing great radiation loss. Any warping of the door or frame does not affect the operation of the door or its sealing of the opening when closed.

The furnace is motor tilted, in all sizes, for pouring, but is arranged so that it can be tilted by hand in emergency if the motor fails to operate. The smaller sizes of furnace are built for hand operation only, if desired. All parts of the tilting mechanism, including gears and motors, are arranged so that they do not come beneath the furnace and therefore there is nothing under the furnace that can be injured in case of a run-out.

The main electrodes are arranged for automatic regulation and also, in every case, so that they can be regulated by hand in case the regulators or motors should require repair.

The importance of power control is universally recognized, especially when refining operations are carried on. In the Booth-Hall electric furnace the power input can be maintained at any point from one-fourth to full load by means of proper voltage reduction and control switches.

In making steel for the ordinary grade of steel castings, the Booth-Hall electric furnace has operated with a power consumption as low as 446 kilowatt-hours per 2,000 lb. (906 kg.) of steel poured, but the average will be between 500 and 550 kilowatt-hours per net ton for continuous operation. In one of the 4-ton furnaces a considerable quantity of low phosphorous pig iron has been made, running over 0·035 per cent in phosphorus and sulphur, also special steels requiring refining with two or more slags, the power consumption, of course, depending upon the degree of refining required.

[The discussion on this paper will be found on page 276.]

APPLICATION OF ELECTRICAL ENERGY TO THE MELTING OF METALS.

By H. A. Greaves.

(*Paper received* 11 *April, and read at a Joint Meeting of* The Institution *and* The Iron and Steel Institute, 8 *May*, 1919.)

The conversion of electrical energy into heat presents a number of problems differing completely from those connected with the production of heat by the usual combustion processes, and owing to the almost unlimited temperatures obtainable electrically, and the absence of combustion products, a new field of development has been opened up to engineers and metallurgists.

The generation of heat electrically is almost entirely carried out by passing a current of electricity through suitable material. As everyone knows, when a current of electricity is transmitted by any substance a certain amount of heat is generated in the substance, depending mainly on the electrical resistance of the material and the current flowing.

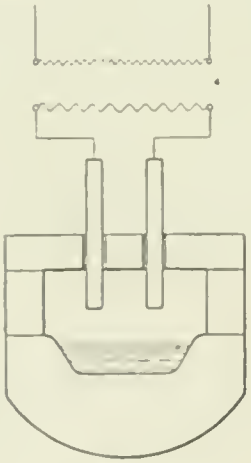


Fig. 1.

Owing to the comparatively low electrical resistance of most metals, it is not feasible, when melting metal in bulk, to increase the current to such a value that the metal reaches a melting temperature by its resistance loss only, except in furnaces of the induction type.

The induction furnace melts the metal by resistance of the charge, and the enormous currents necessary are obtained by arranging the charge in the form of a ring round the iron core of a transformer. This type of furnace is not commercially satisfactory, owing to—

(1) The loss in efficiency caused by the metal being in the form of a ring, and therefore extremely high heat losses occur.

(2) "Pinch" effect, or the breaking of the circuit if the current exceeds a certain value, this effect being due to the mutual attraction of parallel conductors.

(3) The electrical conditions of the induction furnace are unsuited to normal power-supply circuits; a bad power factor is obtained, very low frequency is required, and the furnaces are usually designed to operate on single-phase supply only.

It is necessary, therefore, to use for the generation of heat a resistant material other than the metal to be melted, and the electric arc, which is a column of gas or vapour through which a current of electricity is passing, provides a ready and efficient method of generating a very intense heat in a small space.

The most efficient method of utilizing the heat of the electric arc is obviously to make the material to be melted one pole of the circuit, or, at any rate, part of the circuit, in order that the arc may be in direct contact with the metal. The first furnace using the electric arc was designed with the container as one pole of the circuit, and a carbon electrode over the metal as the other pole of the circuit.

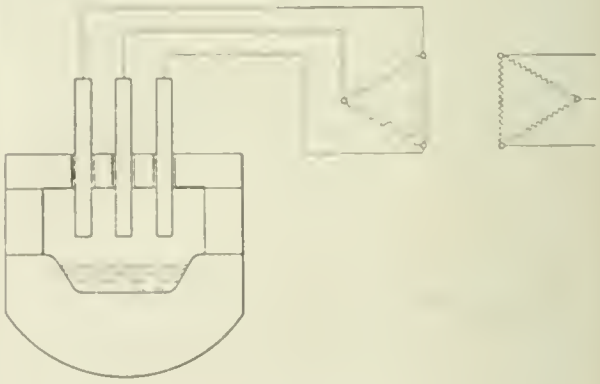


Fig. 2.

In order to use a higher voltage and obtain a better distribution of heat, a furnace was designed with two carbon electrodes over the charge, the current passing from one electrode to the charge, and from the charge to the other electrode, single-phase current being used, as shown diagrammatically in Fig. 1.

In order to utilize three-phase currents, a third electrode was arranged over the charge, as in Fig. 2; furnaces of this kind have been very largely adopted in connection with steel furnace practice, and still form a considerable proportion of the furnaces in operation at the present time.

Without in any way attempting to depreciate the extensive pioneer work carried out by furnaces of this type, there are several inherent disadvantages, viz.—

(1) The electrode currents are not independent of each other.

(2) The heat is applied to the surface of the charge only, and very little circulation of metal is caused.

With regard to (1), it will be seen that if one electrode dips into the charge, or is being driven down into the charge by automatic regulation, while the other electrodes are clear, no current passes and the electrode or electrode-operating gear is liable to be broken while a molten charge of steel takes up carbon from the electrode and upsets the analysis. Many devices have

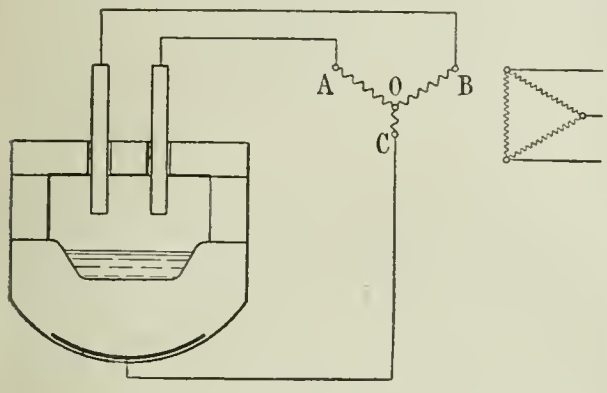


Fig. 3.

been introduced to overcome these objections, but it is well known that most users experience difficulties of this kind, and particularly so when the furnace has an acid or non-conductive lining.

With regard to (2), it will be generally acknowledged that it is more efficient to boil water by applying a gas burner below the water than on the top surface only, as very little circulation of water will result in the latter case. This applies also in the case of an

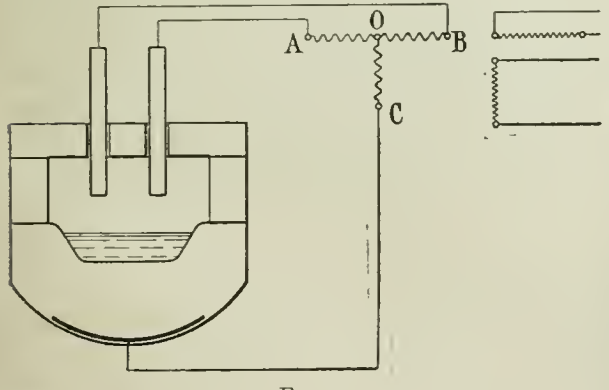


Fig. 4.

electric furnace, and it is a great advantage to introduce a method of causing the metal to circulate freely.

This circulation can be effected by making the hearth of the furnace fairly thick and passing a considerable current through it by using it as one electrode; it is possible in practice to apply from 8 to 10 per cent of the total energy supplied to the furnace in the hearth alone, by using a mixture of magnesite and dolomite and grading it to give the highest resistances near the charge and a negligible resistance towards the outside. Such a hearth is as strong and permanent as any basic hearth that can be made.

Some years ago, in collaboration with Mr. Etchells, the author discovered an electrical law which enables three-phase or two-phase current to be applied to a furnace with an unequal resistance in one of the phases and still maintain a truly balanced load as regards both power and power factor on the primary phases. The connections of such a furnace are shown for three-phase and two-phase working in Figs. 3 and 4 respectively, the length of O C being determined by the resistance of the furnace hearth.

In passing, it may be of interest to electrical engineers to know that an arrangement, as shown in Fig. 5, with an unequal primary star and an unequal secondary delta connected to the furnace will give a truly balanced primary load when the two electrodes are carrying equal currents, the transformer ratios varying according to the relative resistance of the furnace hearth to that

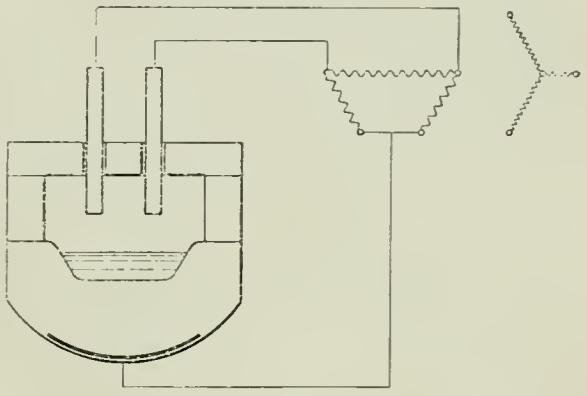


Fig. 5.

of one of the arcs. The author purposely avoids giving mathematical treatment of these rather curious electrical combinations, as they would not interest many of the members.

It will readily be seen that with the systems shown in Figs. 3, 4, and 5, each electrode is independent and regulation of the electrodes, either automatically or by hand, is perfectly simple, while the heat generated in the hearth of the furnace maintains the metal in constant circulation. These systems also give an extremely steady load on the primary phases, due to the buffer effect of the resistive hearth and the phase displacement caused by short-circuit currents.

Up till recently furnaces of the bottom-connection type have not been operated with an acid lining, as such a lining is considered to be non-conductive, although one furnace is made with a water-cooled stud in the hearth to maintain contact with the charge. Water-cooling in the hearth of an electric furnace is surely a dangerous and inefficient makeshift, and the author is pleased to say that after some little investigation a conductive acid lining has been discovered which has operated satisfactorily for some months; this invention, full particulars of which, unfortunately, he is unable to give at present, will also solve the main

difficulties in regulating top electrode furnaces when operating "acid"

A number of furnaces have been built where the full load of the transformers cannot be obtained owing to the drop in power factor with an increase of current, and it has been found in practice that the full-load current per electrode on a 50-period circuit should not exceed 3000 to 4000 amperes.

For furnaces of 5 tons' capacity with transformers of 1500 k.v.a., two-electrode furnaces are satisfactory, but above that size three or, preferably, four electrodes should be used. Figs. 6, 7, and 8 show three combinations of the transformer system illustrated in Fig. 3, E, E, E, E representing the four upper electrodes and H the hearth. In Fig. 6 the current transmitted by the hearth when the electrodes are in equal adjustment will be approximately 0·7 times the sum of the currents in the four electrodes; in Fig. 7 the current transmitted by the hearth will be nil, and in Fig. 8 it will be approximately 0·35 times the sum of the currents in the four electrodes.

It is general practice to provide tappings on the primary windings of the transformers in order to vary the voltage, usually one voltage for melting, one for refining, and one for holding the metal at a constant temperature in the furnace. It is possible, therefore, by suitably connecting the voltage-changing switch to arrange for different degrees of bottom heating effect for the different stages of each heat, the heat circulating

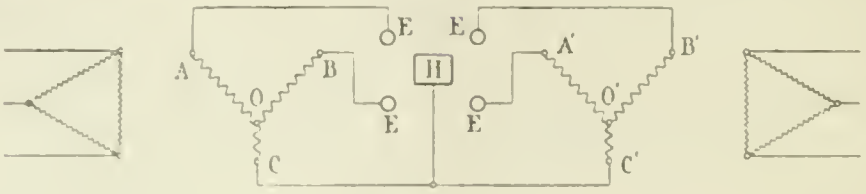


Fig. 6.

are not efficient for steel melting, the output, energy and electrode consumptions, and lining repairs comparing very unfavourably with the direct arc furnaces.

For melting certain metals, however, such as bronze or copper the indirect arc furnace has certain advantages, particularly when melting metals which are volatile at comparatively low temperatures. In such a case to employ a direct arc furnace would result in a very high loss due to volatilization on account of the very hot region of the arc being actually in contact with the metal.

By employing an indirect arc furnace this effect is somewhat reduced, but special means for cooling the walls of the furnace must be resorted to in order to prevent the refractories from fusing at too high a rate and thus render the cost of running prohibitive.

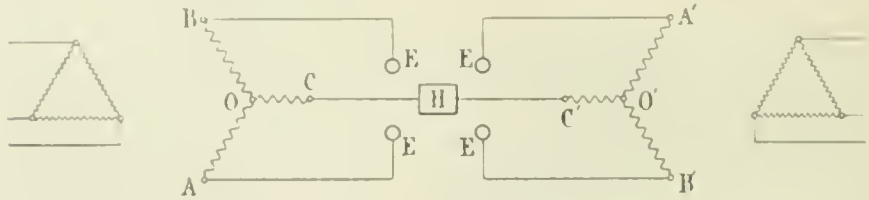


Fig. 7.

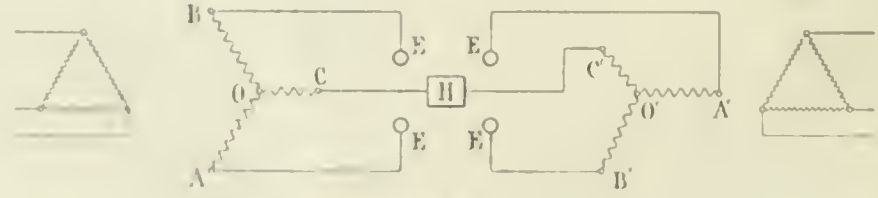


Fig. 8.

The reason for this is that the rays of intense heat from the arc strike directly on the walls, whereas in the direct arc furnace the intense heat is more or less shielded by being partly buried in a crater of slag or metal, which material in addition to acting as a shutter, also rapidly conveys the heat away.

To render the indirect arc furnace a more commercial

proposition, the U.S.A. Bureau of Mines have adopted a method of rocking the furnace in such a manner that the molten charge is constantly washing the walls of the furnace and thus the lining is kept comparatively cool. In addition to this cooling effect, the washing of the metal has a tendency to absorb some of the metal which may have been driven off as a vapour; also the charge is kept well stirred, which results in a very uniform product.

For many kinds of work the arc furnace is quite unsuitable, such as reheating, annealing or melting of metals which have low melting temperature, and even with high melting temperature, when the quantity is small.

For such work the resistance furnace is the best type that can be employed; but where the temperature to be attained is above 1,000° C., the difficulties to be met with are very numerous.

For temperatures below this figure, probably the best element is that made from an alloy of nickel chromium; but for temperatures above 1,000° C., it is necessary to resort to other materials.

In the Baily furnace a trough constructed of a highly refractory material, such as silicon-carbide, is built on the inside wall of the furnace. The trough is filled with a carbonaceous material which forms the resistor. The heat from the material usually travels in an upward direction and impinges on the roof of the furnace which acts as a reflector and reflects the heat down on to the charge. This seems a roundabout method of heating and is calculated to punish the roof materials unduly. In addition to this drawback the carbon of the resistor oxidizes very readily, consequently requires frequent renewal, and thus leads to the trough being gradually filled with residue or ash from the carbonaceous material, which means periodically shutting down for cleaning.

By constant effort to improve the resistor type of furnace a method of construction has been brought out to overcome some of the previous difficulties and improve the efficiency of the furnace. The method consists in forming a hearth or crucible, which acts as the container for the bath of metal, the depth of the bath being relatively small compared with the surface area of the bath. The resistor element, or elements if more than one is required, are arranged suspended above the bath but as close to the metal as possible, only sufficient distance as may be required for stirring or charging being allowed. The heat generated is transmitted to the charge mainly by direct radiation.

The heating element is made of a highly refractory material, and yet not readily oxidizable at high temperatures, nor yet does the material disassociate until an exceedingly high temperature has been attained.

The element itself is built up of a number of sections dovetailed into one another and held in suspension by pressure exercised at the ends of the resistor, the amount of pressure used actually being greater than that necessary to support the element; but as the resistance of the element to a certain extent depends upon the pressure, a margin of variation is allowed for.

This type of element requires no booster transformer or any expensive voltage-changing device such as is employed in most resistive types of furnace, the amount of energy being readily varied by pressure applied to the heater unit in a manner external to the furnace.

Another feature of the furnace is that the elements are renewable even while the furnace is hot.

The construction is such as to make the furnace gastight, which results in an absolute minimum of zinc loss when employed on brass melting.

[The discussion on this paper will be found on page 276.]

ELECTRIC FURNACES IN THE UNITED KINGDOM, 1918.

By R. G. Mercer, Member.

(*Paper received 4 April, and read at a Joint Meeting of* The Institution *and* The Iron and Steel Institute, *8 May*, 1919.)

Introductory.

In preparing this short paper which deals chiefly with the operation and output of the various types of furnaces under actual working conditions, the author wishes at the outset to make it clear that while he is anxious to render the data given as intelligible as possible, he obviously cannot give the names of the users; so, in the tables given below, the furnaces are all numbered and will doubtless be recognized by their respective owners. Furthermore, he cannot, in his present position, show in these tables the makers' names. The data given will, however, show users whose furnaces are not operating as well as they may wish, what their performance and output should actually be.

The author's main object is to give any information possible which may tend to increase the general efficiency of electric steel furnaces in this country.

There are installed or being installed 141 electric furnaces with a total capacity of 112,000 k.v.a. Of these, 24 are or will be used for Swedish substitute, cupro nickel, allundum, manganese copper, and ferro alloys.

The remaining 117 are electric steel furnaces having a total charging and k.v.a. capacity of 384 tons and 98,769 k.v.a. respectively, and a total nominal output of 31,170 tons per month, based on 5 days a week, 4 weeks per month.

Assuming that all these furnaces are working at full load, the total nominal output at the end of a year would be 405,000 tons. It has to be borne in mind, however, that some furnaces only work on day shift, others are shut down or not yet installed, and all those in commission have delays due to furnace or electrical troubles and shop conditions. These delays were in many cases very frequent and serious and are referred to below.

Electric steel furnaces are used for steel castings and ingots, and the following tables give particulars of each and the total number, capacity, etc., of each type of furnace.

It will be noted that the Héroult furnace which was first in the field heads the list so far as number of furnaces and capacity are concerned.

The Electro-Metals furnace which shows the next highest returns came on the market later.

The Greaves-Etchells, which was produced some time after the Electro-Metals, comes third on the list, and the Snyder furnace, which comes fourth on the list, has only comparatively recently been offered to the steel trade.

The Snyder furnace which is used for making acid steel, has to rely largely on the steel maker's requirements as to whether he wants to make acid or basic steel.

The two furnaces marked "Special" were made by the user.

Table 1.

Electric Steel Furnaces in the United Kingdom.

Make	Number of furnaces	Total tons, size	Total k.v.a.	Nominal tons output per month
Electro-Metals ..	27	73	20,274	6,740
Greaves-Etchells ..	26	64½	18,830	5,680
Héroult	45	180½	43,220	13,760
Rennerfelt ..	4	7	1,895	750
Snyder	6	9½	3,150	1,200
Special	2	2	750	280
Stassano	2	2	600	240
Stobie	5	45½	10,050	2,600
Total	117	384	98,769	31,250

The nominal output in tons per month is based on 5 days a week, 4 weeks a month, and the rated charging capacity of the furnace.

Table 2.—Castings.

Electric Furnaces for Castings (Installed).

Make	Number of furnaces	Tons, size	Total k.v.a.	Tons output per month	
				Nominal	Actual
Electro-Metals ..	13	25½	8,130	2,900	—
Greaves-Etchells	4	7	2,050	700	—
Héroult ..	7	10	4,150	1,560	—
Rennerfelt ..	2	5½	1,100	440	—
Snyder	6	9½	3,150	1,200	—
Special	2	2	750	280	—
Stassano ..	2	2	600	240	—
Stobie	1	5	800	400	—
Total ..	37	72½	20,739	7,720	5,019

It will be noted, however, especially in the case of 6-ton furnaces, that the actual charge is in most cases greater than the rated charge. This is more fully dealt with later.

The actual output giving the best month's output

TABLE 2A.

Electric Furnaces for Castings (to be Installed).

Make	Number of furnaces	Tons, size	k.v.a.	Tons output per month	
				Nominal	Actual
Electro-Metals ..	1	2	800	280	—
Greaves-Etchells	4	17	5,450	1,260	—
Héroult ..	4	10½	2,700	980	—
Stobie	2	13½	3,250	600	—
Total	11	44	12,200	3,120	say 2,028
Grand total ..	48	116½	32,939	10,840	7,047

TABLE 3.—INGOTS.

Electric Furnaces for Ingots (Installed).

Make	Number of furnaces	Tons, size	k.v.a.	Tons output per month	
				Nominal	Actual
Electro-Metals ..	12	39½	10,335	3,200	—
Greaves-Etchells	10	14¾	4,710	1,570	—
Héroult ..	32	148¾	34,920	10,720	—
Rennerfelt ..	1	2	600	240	—
Stobie	1	12	3,000	800	—
Total ..	56	217	53,565	16,530	12,906

TABLE 3A.

To be Installed.

Make	Number of furnaces	Tons, size	k.v.a.	Tons output per month	
				Nominal	Actual
Electro-Metals ..	1	5	1,000	360	—
Greaves-Etchells	4	22	4,900	1,650	—
Héroult	1	3½	750	280	—
Stobie	1	15	3,000	800	—
Total ..	7	44½	9,650	3,090	say 2,410

of each furnace is purposely taken, and is 65 per cent of the nominal output (see Table 2).

Assuming that the furnaces to be installed have an actual output of 65 per cent in Table 2, the actual output per month would be 2,028 tons, making a total of 7,047 tons per month, or 91,637 tons in the ladle per annum, for castings, against a total nominal output of 140,920 tons per annum. It will be readily seen from the above figures that the furnaces are mostly working on day shift (see Table 2A).

The actual output is purposely taken from the best month's output of each furnace, and is 78 per cent of the nominal output (see Table 3).

Assuming these had a ratio of 78 per cent actual to nominal output as above, the actual output would be 2,410 tons per month (see Table 3A).

These furnaces represent those sanctioned by the Ministry of Munitions of War and do not include those ordered since November 1918, after which date sanction was not required.

TABLE 3B.

Furnaces (not Working) November 1918.

Make	Number of furnaces	Tons, size	k.v.a.	Tons output per month	
				Nominal	Actual
Greaves-Etchells	4	3¾	1,720	500	—
Héroult	1	2½	700	220	—
Rennerfelt ..	1	½	5	70	—
Total ..	6	6¾	2,615	790	say 716

The actual output would be 716 tons per month on the above assumption.

TABLE 3C.

Furnaces for Castings and Ingots.

Class of steel	Number of furnaces	Tons, size	k.v.a.	Tons output per month	
				Nominal	Actual
Ingots	69	267½	65,830	20,410	16,032
Castings.. ..	48	116½	32,939	10,840	7,049
Grand total..	117	384	98,769	31,250	23,081

These figures go to show that, on the above assumption, we have in this country furnaces capable of producing a total possible output of over 300,000 tons of electric steel per annum with 98,769 k.v.a. behind them.

Taking the average output per month over a period of time we get very different results, as follows:—

	Nominal	Actual	
Castings	7,720	3,557	46 per cent
Ingots	16,530	9,855	59 per cent

TABLE 4.

Nominal Output 70 Tons per Month (80 for Castings).

	1	2	3	4	5	6	7
K.v.a.	250	250	200	250	250	250	250
Size, tons	½	½	½	½	½	½	½
Period, months	1	4½	1	2	4	8½	5½
Class of steel*	HS	HS	Carb.	HS	Cgs.	Cgs.	Cgs.
Number of slags	2	1	1	1	1	1	2
Number of heats	51	313	243	244	163	306	133
Number of hours	149	690	569	316	306	633	198
Number of tons	25	157	136	125	175	176	70
Average:							
Time per heat, hours	2·9	2·23	2·34	1·3	2·43	1·73	3·71
Time per ton, hours	5·9	4·45	4·18	2·57	2·26	3·59	7·1
Tons per heat	0·49	0·5	0·56	0·5	1·07	0·48	0·52
Units per heat	600	443	670	—	857	577	770
Units per ton	1,220	883	1,200	750	793	1,200	1,400
Tons per month	25	34	31	62	44	21	13
Heats per day	2·5	3·5	3	6	2	2	1·3
Best month's output	25	41	40	75	66	38	23
Units per ton	1,220	840	1,140	—	705	1,183	1,400
Heats per day	3	4	3·5	7	2·8	3·7	2·4
Electrode diameter A	4 in.	4 in.	4 in.	5½ in.	4 in.	4 in.	4 in.
Electrode diameter G	—	—	—	—	—	—	—
Electrode, consumption, lb. per ton in ladle	47	18	25	37	17	18	22
Delays, days	2	18	18	—	17	79	3
Basic or acid	B	B	B	A	B	B	B

All these furnaces are on day shift.

No. 5 it will be noted shows an output over the best month of 96 tons. There were 56 heats during this period, so the average weight was 1·7 tons per charge in a ½-ton furnace. The general performance of this furnace is good, though the electrode consumption can be improved, and should come down to 10 or 12 lb. of graphite per ton in ladle, even on day shift.

No. 1 is a case where no meter has been installed against the furnace. The current consumption is, however, estimated to be 750 units per ton.

TABLE 5.

Nominal Output 100 Tons per Month.

	1	2	3	4	5	6
K.v.a.	300	300	300	300	325	360
Size, tons	½	1	1	1	1½	½
Period, months	4½	3	½	4½	4	5½
Class of steel	Cgs.	Carb.	Cgs.	Cgs.	NiCr. Ni, & C	HS & C
Number of slags	1	2	2	2	2	2
Number of heats	479	52	28	108	137	200
Number of hours	1,266	577	152	612	651	780
Number of tons	272	43	37	140	256	216
Average:						
Time per heat, hours	2·66	11	5·4	5·67	4·75	3·9
Time per ton, hours	4·6	13·4	4	4·37	2·54	3·6
Tons per heat	0·57	0·82	1·35	1·3	1·86	1·08
Units per heat	510	1,510	6,040	2,490	1,900	—
Units per ton	900	1,830	5,250	1,950	1,000	—
Tons per month	60	14	74	31	64	40
Heats per day	5·3	1	3	1·5	1·7	2
Best month's output	89	20	—	42	100	56
Units per ton	750	1,480	—	1,680	1,184	—
Heats per day	5·6	1	—	1·5	3	2·6
Electrode diameter A	—	10 in.	—	—	—	—
Electrode diameter G	4 in.	—	3 in.	3 in.	7 in.	6 in.
Electrode consumption, lb. per ton in ladle	28	—	—	20	30	29
Delays, days	11	43	—	52	39	17
Basic or acid	A	B	B	B	B	B

No. 2 had great delays due to furnace troubles and relining and spent most of its time and current in reheating, and is now seldom used.

No. 3 has been shut down and is given to show how much current a furnace can use.

No. 4 will shortly be shut down and is seldom used.

No. 5 had many delays due to failure of supply.

No. 6 is a case where no meter has been installed against the furnace, the current consumption is estimated at 1,170 units per ton.

* [illegible] Cgs. = Crucible; HS = high speed tool; Carb. = carbon tool steel; NiCr. = nickel-chrome

TABLE 6.

Nominal Output 180 *Tons per Month* (200 *for Castings*).

	1	2	3	4	5	6	7
K.v.a.	450	450	450	400	450	450	450
Size, tons	1½	1½	1½	1½	1½	1½	1½
Period, months	3½	4½	3	2	5½	5½	5½
Class of steel	HS	I	I	Cgs.	Cgs.	Cgs.	Cgs.
Number of slags	2	2	2	1	1	2	2
Number of heats	217	229	87	151	447	238	200
Number of hours	826	1,605	431	522	1,383	842	742
Number of tons	359	357	122	222	628	368	331
Average :							
Time per heat, hours	3·8	7	4·9	3·4	3	3·53	3·7
Time per ton, hours	2·3	4·49	3·5	2·3	2·2	2·28	2·24
Tons per heat	1·65	1·55	1·4	1·47	1·4	1·55	1·65
Units per heat	1,420	1,830	1,490	1,330	1,120	1,477	1,532
Units per ton	860	1,180	1,060	950	800	955	925
Tons per month	120	79	40	110	114	67	60
Heats per day	3	3	1·4	3·7	4	2	2
Best month's output	156	100	64	125	180	94	108
Units per ton	785	1,139	920	890	770	1,000	880
Heats per day	4·75	4	2	4	6	3	3
Electrode diameter A	—	—	—	—	—	14 in.	—
Electrode diameter G	6 in.	6 in.	5⅛ in.	4 in.	5⅛ in.	8 in.	6 in.
Electrode consumption, lb. per ton in ladle	—	—	—	—	—	·170	—
	20	40	30	9	21	32	13
Delays, days	29	23	16	4	27	11½	—
Basic or acid	B	B	B	A	B	B	B

TABLE 7.

Nominal Output 180 *Tons per Month* (200 *for Castings*).

	1	2	3	4	5	6	7	8
K.v.a.	520	500	500	500	500	500	500	500
Size, tons	1½	1½	1½	1½	1½	1½	1½	2¼
Period, months	7½	4½	1	4	11½	3	4½	5½
Class of steel	NiCr, Ni, & C	Special Alloy	Cgs.	Cgs.	Cgs.	Cgs.	Cgs.	Cgs.
Number of slags	2	2	2	2	2	2	1	2
Number of heats	473	249	74	126	624	254	416	170
Number of hours	2,457	972	126	556	2,240	929	1,231	949
Number of tons	935	343	127	187	816	355	639	324
Average :								
Time per heat, hours	5·18	3·9	1·7	4·4	3·58	3·6	2·9	5·5
Time per ton, hours	2·62	2·8	0·99	2·97	2·74	2·6	1·9	2·9
Tons per heat	1·97	1·37	1·7	1·48	1·3	1·4	1·53	1·9
Units per heat	2,195	1,370	1,250	1,930	1,300	1,530	1,270	2,710
Units per ton	1,110	990	729	1,300	997	950	830	1,420
Tons per month	124	80	127	47	71	118	130	59
Heats per day	3	3	3·7	1·5	2·5	4	4	1½
Best month's output	179	128	—	64	112	147	173	95
Units per ton	1,000	940	—	1,228	960	890	775	1,220
Heats per day	4	4·6	3·7	2	4	4·7	5·3	2·5
Electrode diameter A	—	—	—	—	—	—	—	4 in.
Electrode diameter G	7 in.	8 in.	7 in.	8 in.	6 in.	10 in.	6 in.	5⅛ in.
Electrode consumption, lb. per ton in ladle	17	26	30	—	26	30	29	15
Delays, days	28	21	7	11	71	16	3	25
Basic or acid	B	B	B	B	B	B	B	B

TABLE 8.

Nominal Output 220 Tons per Month (240 for Castings).

	1	2	3	4	5	6	7	8	9
K.v.a.	600	600	600	600	600	625	650	650	650
Size, tons	2	1½	2	2½	1½	2	2	2	2
Period, months	3½	4½	5½	5½	4	3	5½	4½	2
Class of steel	1	Cgs.	Cgs.	Cgs.	1 & Cgs.	Cgs.	Cgs.	Cgs.	Cgs.
Number of slags	2	2	1	2	2	1	1	1	2
Number of heats	117	356	444	195	114	45	377	249	31
Number of hours	926	1,266	1,605	1,149	676	256	1,201	893	246
Number of tons	202	525	891	442	233	94	702	514	55
Average:									
Time per heat, hours	7·9	3·5	3·6	5·78	5·9	5·7	3·18	3·59	7·9
Time per ton, hours	4·5	2·4	1·8	2·6	2·9	2·7	1·57	1·73	4·47
Tons per heat	1·73	1·47	2	2·26	2	2	2	2	1·77
Units per heat	2,480	1,150	1,337	4,470	1,880	2,560	1,800	1,800	3,160
Units per ton	1,430	780	668	1,970	923	1,280	890	890	1,800
Tons per month	57	116	162	80	60	31·	139	114	28
Heats per day	1·6	4	4	2	1·4	1	3	2·7	1
Best month's output	90	153	229	103	96	41	263	163	—
Units per ton	1,265	745	666	1,870	1,080	1,090	860	920	—
Heats per day	2·5	5·2	5·8	2	2·5	1	3·4	4	—
Electrode diameter (A	5½ in.	—	—	4 in.	—	10 in.	—	—	14 in.
Electrode diameter (G	—	4 in.	4 in.	5½ in.	6 in.	—	8 in.	8 in.	8 in.
Electrode consumption, lb. per ton in ladle	6 in.	—	—	—	—	—	—	—	59
	44	7	7·3	15	16	—	17	29	56
Delays, days	11	12	19	—	54	—	65	45½	—
Basic or acid	A	A	A	B	B	B	B	B	B

TABLE 9.

Nominal Output 220 Tons per Month.

	1	2	3	4	5	6	7	8	9
K.v.a.	600	600	600	600	600	625	650	650	650
Size, tons	2	3	1¼	2	1½	2	2½	4	3
Period, months	5	3¼	3	3½	2	4½	5½	3	7½
Class of steel	C & NiCr	C & NiCr	1	1	HS	C & NiCr	HS	C & NiCr	High C & Cgs.
Number of slags	2	2	2	2	2	2	2	2	2
Number of heats	180	211	79	172	116	126	155	93	328
Number of hours	845	1,487	477	647	498	1,139	824	685	1,676
Number of tons	461	847	90	413	214	671	470	420	1,279
Average:									
Time per heat, hours	4·47	6·57	6	3·18	4·2	8·9	5·43	7·3	5
Time per ton, hours	1·83	1·63	5·2	1·56	2·3	1·69	1·75	1·6	1·3
Tons per heat	2·41	4	1·14	2·36	1·84	5·3	3	4·5	3·9
Units per heat	2,945	2,995	1,970	2,430	—	—	2,800	4,110	2,280
Units per ton	835	746	1,730	970	749	—	920	910	584
Tons per month	92	260	30	118	107	150	85	140	170
Heats per day	1·8	3	1·4	2·5	3	1·4	1·4	1·5	2
Best month's output	105	331	57	132	—	195	127	200	266
Units per ton	720	710	1,350	930	—	—	880	897	625
Heats per day	2	4	2·4	2·5	3	2	2	2·2	3
Electrode diameter (A	—	14 in.	—	14 in.	—	—	—	—	14 in.
Electrode diameter (G	6 in.	—	9 in.	—	6 in.	7 in.	9 in.	8 in.	—
Electrode consumption, lb. per ton in ladle	17	60	—	60	—	17	24	26	47
Delays, days	16	7	—	26	12	39	45	26	5
Basic or acid	B	B	B	B	B	B	B	B	B

TABLE 10.

Nominal Output 280 Tons per Month.

	1	2	3	4	5	6	7
K.v.a.	750	750	750	750	765	800	800
Size, tons	3½	3	3	3	2½	5	3
Period, months	1	3	4½	5	3½	5½	5½
Class of steel	I and Cgs.	C and Cgs.	I and Cgs.	I and Cgs.	Cgs.	Cgs.	Cgs.
Number of slags	2	2	2	1	1	1	2
Number of heats	42	120	224	156	305	267	189
Number of hours	212	656	1,242	815	1,178	1,111	841
Number of tons	110	354	915	427	694	1,020	579
Average :							
Time per heat, hours	5	5·46	5·54	5·2	3·86	4·1	4·4
Time per ton, hours	1·9	1·85	1·35	1·9	1·7	1·08	1·45
Tons per heat	2·6	2·95	4·08	2·73	2·27	3·8	3
Units per heat	2,630	2,620	3,700	2,670	1,820	3,300	3,120
Units per ton	1,000	955	900	977	800	866	1,050
Tons per month	110	118	203	85	198	185	105
Heats per day	2	2	2·5	1·5	4·3	2·4	1·7
Best month's output	—	195	260	97	237	223	128
Units per ton	—	945	940	1,000	720	810	1,020
Heats per day	2	3·3	3·5	1·8	4·8	2·8	2
Electrode diameter A	14 in.	—	14 in.	14 in.	—	—	—
Electrode diameter G	—	8 in.	—	—	8 in.	9 in.	8 in.
Electrode consumption, lb. per ton in ladle	—	23	90	70	12·6	6·5	16
Delays, days	7	27	34	8	9½	16	20
Basic or acid	B	B	B	B	B	B	B

It will be noted that whereas No. 5 was in actual operation on the average 19·6 hours per day with an average output of 198 tons per month, No. 6 working 11·8 hours a day gave an average output of 185 tons per month. The electrode consumption of 6·5 lb. includes breakages.

TABLE 11.

Nominal Output 280 Tons per Month.

	1	2	3	4	5	6	7	8
K.v.a.	750	750	750	750	800	800	850	900
Size, tons	3	3	3½	3	3	3	3	3
Period, months	2	2	3½	3½	4½	3	3½	4
Class of steel	I	I	Cr, and NiCr	I	I	C	NiCr Mang.	I and Cgs.
Number of slags	2	2	2	2	2	2 & 1	2	2
Number of heats	156	112	150	205	77	90	100	114
Number of hours	733	547	837	865	467	625	547	754
Number of tons	487	300	523	704	293	265	354	416
Average :								
Time per heat, hours	4·69	4·8	5·4	4·2	6	6·9	5·47	6·6
Time per ton, hours	1·5	1·6	1·6	1·22	1·59	2·3	1·54	1·8
Tons per heat	3	2·68	3·48	3·4	3·8	2·9	3·54	3·64
Units per heat	2,510	2,650	3,040	2,890	4,100	2,980	4,120	3,360
Units per ton	807	990	870	844	1,080	1,000	1,160	920
Tons per month	243	150	149	300	65	88	100	104
Heats per day	3·9	2·8	2	3	1	1½	1·5	1·4
Best month's output	—	—	207	279	102	138	149	163
Units per ton	—	—	720	817	1,160	1,000	1,050	1,000
Heats per day	3·9	2·8	2·4	4	—	2·5	2	2½
Electrode diameter A	—	14 in.	—	—	14 in.	—	—	16 in.
Electrode diameter G	8 in.	—	8 in.	8 in.	—	8 in.	9 in.	—
Electrode consumption, lb. per ton in ladle	—	—	15	13	97	—	22	65
Delays, days	—	—	—	19	34	102	15	57
Basic or acid	B	B	B	B	B	B	B	B

No. 6—three months' working period from 5 Oct. to 22 Feb., 5½ months.
No. 7 has had 281 tons' output at 925 units in the month, working 19·6 hours per day, 4·8 heats per day.

TABLE 12.

Nominal Output 380 Tons per Month.

	1	2	3	4	5
K.v.a.	1,200	1,200	1,200	1,200	1,200
Size, tons	6	7	6	6	6
Period, months	3¼	1¼	4½	2	3¼
Class of steel	NiCr	Ni & C	I	I	I
Number of slags	2	2	2	2	2
Number of heats	171	70	116	67	128
Number of hours	1,373	573	1,203	745	1,100
Number of tons	1,501	517	1,183	478	873
Average:					
Time per heat, hours	8	8·2	10·37	11·1	8·5
Time per ton, hours	0·91	1·1	1·017	1·56	1·26
Tons per heat	8·77	7·4	10·2	7·13	6·8
Units per heat	5,710	6,899	9,050	7,080	6,870
Units per ton	650	934	896	995	1,000
Tons per month	402	413	252	239	267
Heats per day	2·6	2·8	1·3	1·7	2
Best month's output	552	—	435	338	299
Units per ton	647	—	800	957	990
Heats per day	3	—	2	2·35	2
Electrode diameter A	18 in.	20 in.	20 in.	18 in.	18 in.
Electrode diameter G	—	—	—	—	—
Electrode consumption, lb. per ton in ladle	30	45	86	130	—
Delays, days	5	7	56	15	—
Basic or acid	B	B	B	B	B

No. 1 gave 552 tons in 63 heats of 485 hours in one month. The electrode consumption is excellent for amorphous carbon.

No. 3 furnace had electrical troubles; also electrodes were the chief causes of delay.

No. 4 electrodes gave great trouble and caused great delays.

TABLE 13.

Nominal Output 420 Tons per Month.

	1	2	3	4	5
K.v.a.	1,800	1,800	1,875	1,500	1,500
Size, tons	7	6	8	7	7
Period, months	11½	2½	1½	3	2¼
Class of steel	NiCr	I	I	I	I
Number of slags	2	2	2	2	2
Number of heats	331	114	45	104	105
Number of hours	3,015	756	415	1,048	1,063
Number of tons	3,015	786	437	748	953
Average					
Time per heat, hours	9·1	6·63	9·2	10	10·1
Time per ton, hours	0·99	0·96	0·95	1·4	1·11
Tons per heat	9·2	6·9	9·7	7·2	9·07
Units per heat	8,700	5,710	9,000	7,450	6,500
Units per ton	945	828	925	1,035	715
Tons per month	265	314	202	249	381
Heats per day	1·5	2·3	1·5	1·7	2·3
Best month's output	400	372	365	300	422
Units per ton	950	800	940	1,000	677
Heats per day	2	2·7	2	2	2·4
Electrode diameter A	18 in.	—	20 in.	20 in.	18 in.
Electrode diameter G	—	12 in.	—	—	—
Electrode consumption, lb. per ton in ladle	65	—	44	—	100
Delays, days	77	—	10	—	11½
Basic or acid	B	B	B	B	B

It is rather a coincidence that comparing these with the best month's outputs there is a difference in each case of 19 per cent. Delays due to breakdowns, changing roofs, relining, etc., are largely responsible for this.

Electric Furnace Log Sheets.

On visiting the various steel works in this country the author found that while some users kept proper records of the operation and output of their furnaces, others confined themselves more to the output and kept no proper records of current and electrode consumption or causes of delays. Some indeed appeared to treat these as a matter of course, notwithstanding their anxiety to get output. This sort of feeling was good neither for the electric steel trade of the country nor for the maker or designer of the furnace. When keen competition set in, the steel maker might find his furnace out of commission and, unless the furnace maker made his furnace as fool-proof, reliable, and efficient as possible, he would find he was doing harm not only to the electric steel trade development in this country but also to himself in particular.

It was decided therefore to send out electric furnace log sheets to all users and to ask for weekly returns to be made to the Ministry of Munitions. This sheet was based on the Héroult furnace log sheet of which Mr. Campbell kindly supplied a copy.

To meet the wishes of the steel makers, who rightly pointed out that while anxious to give the Ministry the fullest possible information it was very difficult, especially where several furnaces were installed, to find time or staff to fill them in, in view of the number of other returns they already had to make to different Departments of the Ministry, this log sheet was later replaced by a fortnightly return with condensed particulars as shown in the log sheet reproduced in the Appendix to this paper. The main difference between the two log sheets was that instead of giving full particulars of each individual heat, the total number over a fortnight is now given. These, with the particulars previously given, were sufficient for the requirements of the Ministry and enabled the latter to note especially those furnaces which were not operating well and the reason for this. The author desires to thank the electric furnace proprietors for the great trouble they have taken in making these returns as complete and comprehensive as possible.

From the returns given in these log sheets he has been able to insert the figures given in Tables 4 to 14 inclusive. These figures, taken over a period of one to six months, show the comparative performance of the same or different types of furnaces working as nearly as possible on the same class of steel and under similar conditions in the various steel works.

In making comparisons the author considers it to be necessary to take furnaces having the same k.v.a. capacity and not the rated charging capacity in tons, and it will be noticed that they are entered on this basis.

The heats per day in the tables are the average number of heats taken over the whole period of 20 days a month, and include "delays."

Under "best month's output" the average number of heats per day are shown with "no delays."

Table 14.

Nominal Output 600 Tons per Month.

	1	2
K.v.a.	2,500	3,000
Size, tons	10	12
Period, months	3½	6¼
Class of steel	Ni, CH	Ni, CH, and C
Number of slags	2	2
Number of heats	106	331
Number of hours	818	2,039
Number of tons	900	3,575
Average:		
Time per heat, hours	7·7	6·16
Time per ton, hours	0·9	0·57
Tons per heat	8·5	10·8
Units per heat	8,200	9,657
Units per ton	966	890*
Tons per month	257	572
Heats per day	1·5	2·6
Best month's output	357	791
Units per ton	945	869
Heats per day	2·3	3·6
Electrode diameter A	18 in.	—
Electrode diameter G	10 in.	10 in.
Electrode consumption, lb. per ton ladle	30	12·9
Delays, days	—	29
Basic or acid	B	B

* Includes all steelworks' auxiliaries, and the rating would be 700 tons per month on the basis of 3 heats of 12 tons, say 35 tons per day, 20 days per month. This furnace has had as much as 1,010 tons' output in one month in 1917.

Nominal Output.

After a careful comparison of the various sizes and types of furnaces, the author has arrived at the following particulars, setting forth the size, k.v.a. capacity, and nominal output of each.

Table 15.

Ratings of Electric Furnaces.

Ingots or Castings	Size, tons	k.v.a.	Average hours per heat	Number of heats per day	Nominal tons per month of 20 days
Ingots	½	250	2·75	7	70
Castings	½	250	2·25	8	80
Ingots	1½	500	3·25	6	180
Castings	1½	500	3	7	200
Ingots	2–2½	650	4·25	5	220
Castings	2–2½	650	3·5	5	240
Ingots	3–3½	850	5·75	4	280
Castings	3–3½	850	4·75	4	280
Castings	5	1,000	4	5	500
Ingots	6	1,500	7·5	3	360
Ingots	7	1,800	7·5	3	420
Ingots	10	2,500	7·5	3	600
Ingots	15	3,000	7·5	3	900

The nominal output per month is based on the assumption that the weight of charge is equal to the

rated charging capacity of the furnace. In actual practice however, this is not the case in many furnaces, as will be noticed in the preceding tables. The 6-ton furnaces, for instance, take from 0·8 to 10·2 tons per charge on the average. Consequently the actual output is increased, though on the other hand the heat period would increase and the average number of heats per day might be less than the above estimate. The author sees no reason, however, why the above outputs should not be easily reached under proper conditions, and these call for continuity of working and reliability of plant and the efficient working of the same.

Delays.

Continuity of working greatly depends, of course, on the volume of business, but reliable and efficient working depends on the furnace being as reliable, efficient, and fool-proof as possible. Assuming it has these very rare essentials, and a gang which takes an intelligent interest in what should be regarded as a good tool, it is in turn relying on what is known as "shop conditions," such as waiting for the crane, etc. While it is difficult where there are a number of furnaces working together to arrange things so that they may be teemed as and when ready, it should not be difficult for a single furnace to get this necessary attention, for the want of which the refractories suffer, current is wasted, and the gang is kept waiting.

Failure of electric power supply.—Failure due to breakdown of generating plant and lack of spare plant occurred in one or two cases.

The generating stations were working at their maximum capacity and were at times severely overloaded, and there were few opportunities for overhauling the boilers and other plant. The result was that when shortness of supply happened the first plant to be shut down, with little or no notice, was the electric furnace. It used a large amount of current and was consequently easier to shut down than a lot of small and not so important users.

There is no doubt that all the users of electricity supply were doing important work during the war, but very much less consequential damage and interference would have resulted if the furnace user could have been kept going until he had at any rate a chance of clearing his furnace so as to prevent a possibility of freezing. When it was pointed out to the electrical engineer how important it was to give the furnace user an opportunity of doing this and to find out from him how long it would take to teem, the engineer always showed his keen appreciation and, although he was in these cases at his wits' end to try to accommodate everybody, he most certainly gave the electric furnaces on his mains first consideration. The author thinks a debt of gratitude is due to the various corporations and other electric supply departments for the way they carried on under difficult conditions. Like the Navy they worked silently, and their existence was chiefly brought to mind when anything adverse happened and supply was even temporarily cut off.

Breakdown of furnaces.—Delays due to this cause have been far too frequent. In the author's opinion the tilting gear and general arrangement of electrode feed-gear on certain types have not been designed to withstand the conditions in a steel works. He has many records of stripping on the tilting gear, resulting in very narrow escapes in some instances. He also has records of stripping of the electrode-raising and lowering gear, with the result that the gallows arm falls right down, with consequent damage to the furnace and very possible transformer troubles (referred to later).

It is very comforting to state that the makers concerned have eliminated or are eliminating these bad features. One maker has indeed redesigned his furnace and has, on furnaces now in course of manufacture, made radical alterations and improvements in these and other features. The other makers concerned are making important alterations, but it is not proposed to mention these in this paper.

If the reliability can be improved it will certainly pay the user to have his furnace brought up to date as far as possible (if he has not already done so, and there are cases where this has happened). The result will be that the user can concentrate on making steel without much fear of breakdowns. He will turn the steel out at a cheaper rate per ton, for he will not only save all the "kilo-units" used for heating up, but will also reduce his electrode consumption and prolong the life of the roof and linings.

Water-cooled collars.—These at the electrode entrance in the roof have been a source of constant trouble and delays. Their breakdowns are undoubtedly due chiefly to failure of water supply, but many installations are now complete with a tank placed above in a suitable position, the tank being kept filled from the water mains or other source, so that in the event of the main supply being shut off for any reason, there is a sufficiency to carry on with.

Electrode holders.—Electrode holders of certain types also give a lot of trouble. Personally, the author has little or no use for a water-cooled electrode holder; for in his opinion its use is an admission that it is exposed to the hot gases coming through the roof at the electrode entrance, which therefore has no suitable economizer or seal, or that it has not a proper electrical contact around the electrode. If electrodes (and especially amorphous carbon) are operated at a proper current density, and assuming they are not of inferior quality, the holder should be able to carry the necessary current without undue heating. Against this it may be argued, and with some reason, that where, say, a furnace is fitted with 14-inch amorphous carbons, which at a current density of 25 amperes per square inch should carry about 4,000 amperes each, the user nearly always runs them at 5,000 or 6,000 amperes. The user may say, in explanation, that he cannot otherwise get his heat in the furnace (there is plenty outside). The answer is that he should either put in a larger electrode if the furnace can take it or one be got for, say, 8-inch graphite, which with a current density of 100 amperes per square inch will enable him to run at 5,000 amperes per phase. It may further be argued (and again with some reason) that amorphous carbons are very often of inferior quality. This is the case, and it very often happens that while one batch may be good the very next batch out of the same heating furnace may be very inferior.

Everyone who has used them knows what he may expect. It is not comforting for lumps of, say, 18-inch carbon to break off in the furnace. It is not easy to take them out of a 1¼-inch hole, and it does not console the user even if he is making high carbon steel to have such happenings. The author knows of a case where over 1½ cwt. of amorphous carbon was used to the ton of steel in the ladle, which was immediately made into scrap ingots.

The following table, showing the total amperes which amorphous or graphitic carbons should carry at a current density of about 25 and 100 amperes per square inch respectively, may be of use.

TABLE 16.

Diameter of electrode (in.)		Amperes per electrode	
Graphite	Amorphous	Graphite	Amorphous
5½	10	2,000	2,000
6	14	3,000	4,000
7	16	4,000	5,000
8	18	5,000	6,500
9	20	6,500	7,800
10	—	8,000	—
12	—	11,000	—

There is no doubt whatever that some of the existing types of electrode holders are fairly reliable and efficient (without water cooling) where a reliable electrode economizer is fitted. The great difficulty is to find an economizer which will stand up in existing furnaces of the gallows-arm type fitted with amorphous carbon electrodes. In existing furnaces the gallows arm comes down so close to the roof that a comparatively shallow economizer has to be employed.

The makers of the Greaves-Etchells furnace were, the author thinks, the first to tackle this problem seriously, and they were followed immediately by the makers of the Electro-Metals and Héroult furnaces. Many types have been tried, with good, bad, or indifferent results.

The problem is nothing like so difficult with graphitic carbon electrodes, as these do not suffer from oxidation to anything like the same extent. Economizers which were unsatisfactory with amorphous carbon behaved well up to a certain point, but fell down either due to failure of the water supply or because the man in charge neglected to look after them. These self-adjusting economizers demand attention periodically and are not sufficiently fool-proof. The author's view is that after the maker has done his best to improve an existing furnace by such an addition, it is up to the user to see that proper care and inspection of the same are practised. The whole question of "human element" is by far the most important in the operation of a reliable furnace.

Of the gallows-arm type of furnace the Snyder can claim over a period an electrode consumption as low as 7 lb. of 4-inch graphite per ton of steel in ladle. The Héroult, Greaves-Etchells, and Electro-Metals, have with economizers each shown a graphite consumption, over a period, of 13 lb. per ton, which is good but will, the author hopes, be improved still further.

Of the furnaces having no gallows arm the Stobie shows an electrode consumption of 9-inch graphite as low as 6·5 lb. per ton over a period of 5½ months.

Low-tension conductors.—These have not in all cases received the necessary attention in the past. The author's opinion is that a current density of 750 amperes per square inch is ample for copper strip, for they are nearly sure to be run at a higher rate in actual practice. The maker should himself be responsible for all joints being properly made in the first instance and should instruct the user to have them periodically inspected.

Talks with the qualified electrical engineer in charge on I^2R losses, reactance, etc., may be very useful, but to the ordinary man a knowledge that hot joints mean bad joints has, to the author's knowledge, had greater practical effect.

Transformers.—These are, after all, the most important part of the furnace installation, for a breakdown of one (unless there is a spare at hand) involves in nearly all cases a considerable delay of anything up to, say, 2 months. Until recently, two transformer makers have had the bulk of the furnace business. Breakdowns of both makes have occurred. In the early days these were no doubt due to the fact that the makers did not appreciate (as they did very soon after) the very heavy service their apparatus would be called upon to stand up to. They did not know what heavy surges the transformers would be liable to during the melting-down period; on the other hand, transformers were in some cases of insufficient capacity. The furnace maker may have felt that the guarantee of 20 per cent overload continuously would make them ample. At any rate breakdowns occurred. The transformers were then greatly improved both mechanically and electrically and by degrees transformers of a bigger k.v.a. capacity were installed, but, notwithstanding all this, breakdowns, though less frequent, happened owing to causes quite outside the transformer maker's control. Here are two examples:—

(1) A furnace had practically a dead short-circuit and the oil switch which was close to the furnace refused to trip, the gear being choked with grit.

(2) The transformer was placed in a chamber underground which had forced ventilation but no spare motor-driven fan. The fan failed for want of oil, and the furnace carried on till the transformer failed.

Automatic voltage and current regulators.—These are going to help not only the transformers but also the power supplier. The regulators can be put into commission direct on to a cold charge without any hand control. The electrodes can be rapidly withdrawn on the occasion of very heavy overloads. The result is a very good load chart. The Woolwich Arsenal has a set running in conjunction with one of two 6-ton 2,000-k.v.a. Greaves-Etchells furnaces.

The author has confined this paper to electrical steel furnaces, and so does not propose to deal with the 24 arc furnaces referred to above. Neither does he deal with furnaces of the resistance type such as those

used for carbide and laboratory purposes, or the small furnaces now coming into use in this country for heat-treatment purposes. He thinks, however, that some day we may have large resistance furnaces suitable for heating guns, turbine and engine shafts, etc. One of the great difficulties experienced with large furnaces is due, he understands, to thermal expansion and contraction of the parts, and to the cost of repairing and replacing the heating units. But he believes these have been or are being overcome, and we should then have furnaces which would give uniform heating throughout the charge and with little scaling. Comparing our total of 117 electric steel furnaces with those installed in the United States and Canada, the author notes from the *Iron Age* that America in January 1919 is credited with 287, which includes 3 induction furnaces (there are none in operation here so far as the author knows) and Canada is credited with 43 furnaces.

In conclusion the author hopes that when all our furnaces are in full swing again their output efficiency may be at least as good, over a period, as those shown under "best month's output" for each type of furnace. In other words, that the 10 per cent difference between the two may, if not actually disappear altogether, at any rate be materially reduced.

The author thanks the makers and proprietors of furnaces for their kindness and the information they have so willingly given him, which information, coming as it did from two sources, namely the maker and the user, has enabled him to give the above data and particulars, together with his own impressions concerning the operation of furnaces in general. And he trusts that it will be of practical use to both, with the result that, so far as electric steel is concerned, the great steel trade in this country may be second to none in quality and output per furnace.

APPENDIX.

REPORT E.F.

ELECTRIC FURNACE LOG SHEET.

Name of Firm..... *Fortnight ending Saturday*.....191 .

Address.....

Number of Charges	Total Number of Hours during which Current was on	Total Weight of Charges (including additions) Tons	Cwt.	Qr. (Lb. not required)	Kilowatt Hours: Meter Reading at *beginning* of Fortnight	Meter Reading at *end* of Fortnight	Difference between the Two Readings, i.e. Kilowatt Hours used during the Fortnight	Kilowatt Hours per Ton, i.e. Kilowatt Hours divided by Total Weight of Charges (including additions)

No. of Furnace .....

Make of Furnace .....

Size of Furnace (Tons) .....

Kva. of Furnace .....

Dia. of Electrode { Graphite or ..... / Amorphous..... }

No. of Electrodes used during Fortnight .....

Lining, Basic or Acid .....

Ingots or Castings.....

If "Ingots" state class of Steel below :—

.....

Registered .....

Entered { (N)..... / Y..... }

REMARKS.

Give here full particulars of any Stoppages due to failure of Electrodes, Energy, Water, or any other cause.

This form is to be forwarded each Fortnight in the envelope supplied, to :—

The Controller of Forgings and Castings,
C.F. & C./Stats.,
Ministry of Munitions of War,
8 Northumberland Avenue,
London, W.C. 2.

Telegrams: C.F. & C./Stats., Munorgize, London.

Telephone: Victoria 9210, Ext. 177.
(For Trunk Calls):
"Munitions, Victoria, London."

NOTE.—Should your Furnace for any reason be out of commission during the entire fortnight for which this return is due, please send in your report as usual, marking it as "Nil," and giving the reason for the stoppage.

Signature .....

Date.....

A NEW TYPE OF ELECTRIC FURNACE.

By Axel Sahlin.

(*Paper received 23 September, 1918, and read at a Joint Meeting of* The Institution *and* The Iron and Steel Institute, *8 May, 1919.*)

Introduction.

The electric furnaces hitherto constructed may be divided into three different groups, viz.

(*a*) Induction furnaces;
(*b*) Furnaces with a free-burning arc; and
(*c*) Furnaces relying on a direct arc between the metal and the bath.

The first-mentioned type of furnace is now only occasionally found.

The free-burning arc furnaces have found favour, especially for work where it is desirable to avoid any chemical reaction between the carbon in the electrodes and the bath. They have a decided advantage in giving the means of heating the cold furnaces without the introduction of any charge and by the arc only.

On the other hand, they have the disadvantage that, as soon as the bath is formed, the heat is transmitted to the surface only and no circulation is set up in the molten metal.

Many furnaces of this type have suffered from defective and weak mechanical construction. On that ground some users have preferred direct arc furnaces, in spite of the disadvantages of heavy and cumbersome electrodes, furnace roofs pierced by large holes, and the necessity of using a source of heat other than the electric current to bring the furnace up to melting temperature.

The furnace which is the subject of this paper has been designed with a view to embodying the advantages of both the direct arc and the free-burning arc furnaces, at the same time avoiding as far as possible the disadvantages of both.

Description.

The furnace is built as a circular ladle with contracted top and dished bottom. The shell is made of heavy steel plates, riveted together with $\frac{7}{8}$-inch rivets closely spaced. The plates are perforated by $\frac{3}{8}$-inch drilled holes, spaced about 12 inches apart and serving as vents for moisture contained in the lining. The top rim is reinforced by a heavy flat hoop riveted to the shell plates. The steel casting trunnions are riveted to the shell and rest in bearings set so as to allow for expansion and alignment. To the overhanging end of one trunnion is keyed a crank which, by means of an enclosed screw, running in oil, working in a swivelled crosshead and turned by hand-wheel (or, for larger furnaces, by motor) serves to tilt the furnace to any desired angle.

The bottom of the furnace is made up of a layer of coke dust and tar rammed in, supporting double layers of brick. On top of this is rammed and fixed in successive layers a hearth consisting of burnt dolomite and tar for basic operation, or of ganister in case the acid process is adopted. Supported and resting on the firebrick, outside the hearth, is placed a circular lining backed by a heavy insulating layer of asbestos sheet and formed of circle-bricks laid with ground joints and thin mortar. This lining may be made of magnesite brick for basic process, or of silica brick for acid process. In the lining are placed on the same vertical lines two holes for each pair of electrodes, and one door opening which serves both to charge the furnace and to pour the steel. For larger furnaces one tapping hole and two charging doors would be a better arrangement.

On top of the contracted top of the side lining rests the dome-shaped roof built of basic or acid brick fitted in a circular steel frame, forming a rigid skewback. The roof joint is made of a layer of powdered dolomite or ganister spread on top of the side wall. The roof can be removed by crane without delay, and replaced by another preheated roof held in readiness to take its place. As it is found that the portion of the roof opposite to the arcs is affected more readily than the portion nearest to the electrodes (which is protected to a certain extent by the shadow of the latter) the roof can be turned round to any angle desired. Thus, when the weakest portion is getting thin, the life of the roof can be prolonged by exposing to the fiercest heat the section of the roof hitherto more protected.

It is also possible to charge the furnace through the top by removing the roof while the charge is put in place.

Electrodes.

The electrodes are graphite or carbon electrodes, of cylindrical form, extended as they are burnt away by screwing a new section of electrode to the rear end of the electrode in operation. The joint is made by threaded dowels of graphite. The electrodes slide through water-cooled electrode holders made of steel pipes welded to rings at the front and back ends. Nozzles for water supply and discharge are tapped into these rings, and are connected with rubber hose to the water mains. The electrodes are wrapped in sheets of asbestos, mica, or fibre, and are thus insulated from the furnace body.

The electrode cooler with its insulation is placed between the fixed upper and sliding lower jaws of a clamp which is pivoted to a frame bolted to the furnace shell. A wedge placed beneath the lower jaw of the clamp causes it to grip and firmly hold the insulated cooler with the electrode sliding through the same.

The top part of the clamp is extended outward, forming a support and U-shaped guide for the slide

which grips the rear portion of the electrode. In the hollow interior of the U-shaped guide works a screw which engages against a nut held in place by prongs extending from the electrode holder. If the screw is turned, the electrode holder is moved toward or away from the furnace, advancing or retiring the electrode. The upper portion of the electrode holder is insulated from the grip by a sheet of fibre. The lower swivelling portion of the grip is closed and tightened by an eye bolt with hand-wheel nut. Both halves of the grips are water-cooled, and are fed through nipples connected to the water mains by rubber hose. Both grips are made with an extending wing, to which is bolted the bronze cable socket which receives the end of the cables transmitting the current from the switchboard to the electrode. Both the swivelled guides are adjusted in a vertical sense, controlling at will the inclination of the electrodes.

Electric Arrangement and Wiring.

The number of electrodes proposed is as follows:—

For a furnace hearth		
up to 3 ft. 6 in. diameter	.. ..	1 pair
from 3 ft. 6 in. to 5 ft. diameter	.. ..	2 pairs
from 5 ft. to 7 ft. diameter	.. ..	3 ,,
from 7 ft. to 9 ft. diameter	.. ..	4 ,,
from 9 ft. to 11 ft. diameter	.. ..	6 ,,

This number can be modified according to circumstances.

The electrodes should be preferably of graphite, varying from 2 inches up to 6 inches diameter, according to the size of furnace and the amount of current. Each pair of electrodes enters the furnace in the same vertical plane, but at different and adjustable angles.

The upper electrodes are supplied with current. The lower electrodes, as well as the furnace body (and, if the furnace is going to be used largely for refining work, a bottom electrode bedded in the hearth) are connected with the common of the transformer, or earthed.

For a one-pair furnace direct current or one-phase alternating current is used.

For a two-pair furnace it is preferable to employ two-phase current, generally obtained by three-phase transformers arranged in Scott's coupling.

For a three-pair furnace three-phase current is used, one phase being coupled to each upper electrode.

For furnaces with more than three pairs of electrodes, groups of two pairs are coupled in parallel, therefore, a four-pair electrode furnace uses two-phase current, whereas a six-pair furnace should be supplied with three-phase current. If for any reason it may be found desirable, the upper electrodes can be earthed, and the current can be supplied through the lower electrodes. A bottom electrode bedded in the hearth may be used or not. It is useful when refining because, as the lining material gets very hot, it becomes a good conductor and passes the current through the bath into the bottom electrode when using the direct arc.

The pressure of the supply should preferably be transformed to 100 volts which, by plugs on the transformer, may be reduced at option to 80 or 70 volts.

The connections for a two-pair furnace are shown in Fig. 1. To avoid any chance of shock to operators, it is advisable to place a wooden operating platform over the floor at the back of the furnace

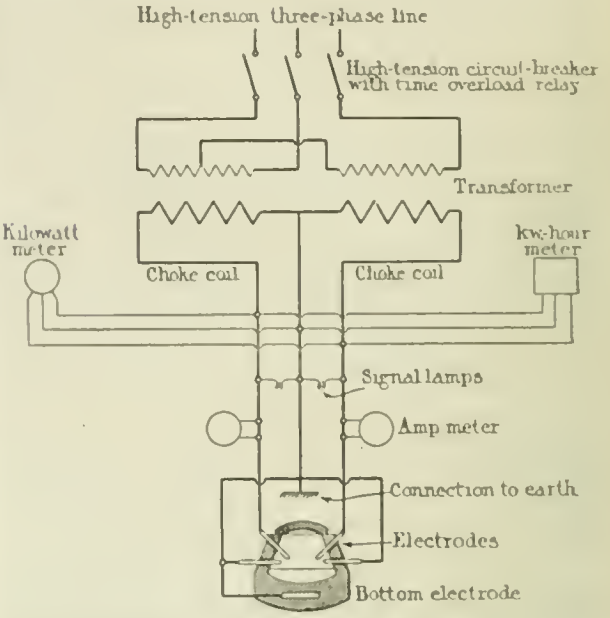


Fig. 1.—Diagram of wiring of a two-pair Sahlin furnace.

around the electrodes. All the electrodes are distributed around the half of the circumference of the furnace opposite to the tapping hole and charging doors. For the smaller sizes of furnaces, the electrodes are fed forward by hand-wheels.

The current taken is observed by reading kilowatt meters placed on a switchboard suitably located, and receiving the feeders from the transformers. It seems to me an advantage to provide choke coils to steady the current.

Operation.

Assuming that the furnace is to be used for melting and refining steel, the first operation is the heating of the furnace to the proper temperature. This is effected by turning on current and gradually advancing the points of the convergent electrodes of each pair until an arc is formed. Experiments have proved that as long as the points of the electrodes are at a certain distance from each other an arc is formed

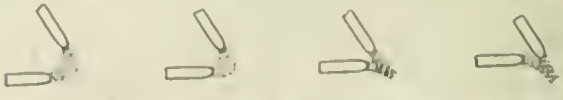


Fig. 2.—Direct arcs observed with different positions of electrodes.

between the two electrodes. As the electrodes approach each other this arc bends outward, forming a loop. If the distance is still further reduced, the loop breaks and the arc rushes forward, sweeping downward toward the surface of the metal like a broom. If the top electrode is advanced beyond the bottom electrode, the broom is deflected downward (see Fig. 2). The

form and direction of the arc can easily be modified by altering the angles of the electrodes and their relative position to each other. The free-burning arc heats the furnace while empty.

The second operation would be the charging. When the furnace is heated, current is taken off, and the electrodes are drawn toward the back wall of the furnace to prevent their being injured, while the material to be melted is thrown or pushed into the furnace through the charging door, or eventually through the furnace top, the roof having been removed. As soon as the charge has been placed in the furnace, the electrodes are advanced. Experience has shown that numerous momentary arcs are formed between the upper electrodes and the charge, but as this latter is melted away in the vicinity of the electrodes, the regular free-burning "broom" arc is formed between the two electrodes and the working of the furnace settles down to normal. The radiation and reflection caused by the free-burning arc are most effective for rapid melting. As, however, the bath is formed, this kind of arc reaches only the slag-covered surface of the metal, causing but little circulation in the interior of the bath. At this point, therefore, the free-burning arcs are broken by the retirement of the lower electrodes and a direct arc is formed by the advancing of the upper inclined electrodes toward the surface of the slag. If the bottom electrode is employed, the current will penetrate toward this bottom electrode which is earthed. The furnace is now working on the lines of a Girod furnace, and creates an electric arc which causes a rapid circulation in the bath and direct transfer of heat to the metal.

In furnaces with more than one pair of electrodes, it is possible to have some of the electrodes produce a direct, and some a free-burning arc, thus making use of the effective radiating and reflecting action of the free-burning arc, at the same time as the bath is agitated by the direct arcs.

Special Work.

For use as a heating furnace for very high temperatures such as are required for the production of graphite, for the calcining of magnesite, for the crystallizing of bauxite, for special crucible work, and for other similar objects, it is proposed to suspend the furnace shell containing the side walls and roof with the electrodes and the electrode mechanism from four lifting rods, operated by electric motor, hydraulic cylinder, or windlass. The bottom of the furnace (which for this work does not require any bottom electrode) would be placed on a truck. On this portable bottom would be placed, in proper arrangement, the material to be heated. The loaded truck being placed beneath the furnace body, this would be lowered on to the truck enclosing the pile of material. A free-burning arc would now be started between the electrodes in each pair, and the furnace would be brought up to the required temperature. The material having been thoroughly heated or calcined, the furnace body would be lifted from the truck, which would be run away to give place to a second truck loaded with fresh material. The loaded trucks could be preheated in a gas-fired furnace before the bottom was placed under the electric furnace. This procedure has been described only as an indication of a use for the electric furnace, filling a long-felt want, but the actual arrangement of the plant would, no doubt, be different for each case and should be separately studied.

Advantages.

It will be found that the furnace, as above described, is of a very strong construction—rigid, simple, and durable. All the surfaces of the brick linings are convex, and the walls will therefore be held in position. The surface of the melting room, confined by spherical and cylindrical walls, is the smallest possible for the largest volume, and the amount of brickwork in the furnace is therefore reduced to a minimum. The electrodes are easily secured in place, adjusted, advanced, or retracted by means of hand-wheels. There are no bolts or nuts manipulated by wrenches used in the adjustment of the furnace, every operation being carried out by hand-wheels or cotters. The roof is solid, without any openings, removable and exchangeable in a minimum space of time. The furnace can be run either with free-burning arcs, with direct arcs, or with free-burning and direct arcs working simultaneously side by side. Changes are made without cutting off the current.

When the furnace is employed as a free-burning arc furnace no chemical reaction between carbon of the electrodes and the bath takes place. The overhanging length of the electrodes is comparatively short, and the arcs are formed fairly close to the circular furnace walls, being directed inward and downward toward the centre of the furnace.

The Sahlin furnace has not yet been placed on the market owing to the difficulty of obtaining a permit for its construction during the war, but a furnace is now being built in Great Britain intended for the production of steel ingots and castings.

[The discussion on this paper will be found on page 276.]

LARGE ELECTRIC STEEL-MELTING FURNACES.

By Victor Stobie.

Paper received 3 *April, and read at a Joint Meeting of* The Institution *and* The Iron and Steel Institute, 8 *May*, 1919.)

Summary.

1. Scope of paper.
2. Wiring diagrams and shapes of furnaces.
3. Arc phenomena.
4. Transformers.
5. Automatic electrode regulators.
6. Power factor.
7. Electrode considerations.
8. Circulation of bath.

Scope of Paper.

The early history and development of electric furnaces are a matter of general knowledge, and are not dealt with in this paper.

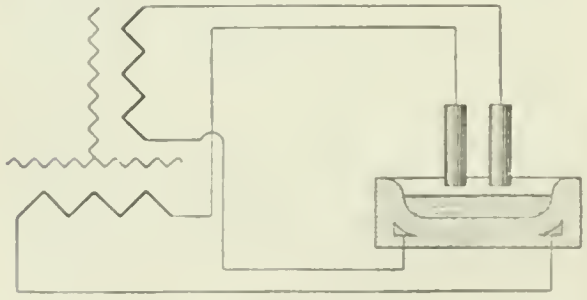


Fig. 1.

The author's commercial and technical experience with small and large electric arc steel-melting furnaces has led him to favour the latter for ingot making on account of the more advantageous costs and conditions of working of large units. The smaller furnaces have a very large field in foundry work. Observations will be confined mainly to the technical requirements of large plant and to some interesting phenomena on all furnaces.

Wiring Diagrams and Shapes of Furnaces.

The wiring diagrams (Figs. 1, 2, and 3) give what the author considers to be the best connections for three sizes of furnaces.

Fig. 1 is for furnaces up to 6 tons' capacity: two-phase current, each phase maintained entirely separate from the other, with one end of each phase connected to separate electrodes above the bath and the other end of each phase connected to separate electrodes embedded in the hearth of the furnace at opposite ends of the furnace to their relative top electrodes. This arrangement gives centrally the requisite bottom heating for small furnaces and is characterized by the crossing of the currents in the direction of flow through the bath.

Fig. 2 is for furnaces from 6 tons' up to 24 tons capacity: two-phase current, each phase maintained entirely separate from the other, with each end of each phase terminating in an electrode above the bath. Long experience has shown that bottom electrodes, whilst essential in small furnaces, are very undesirable in large furnaces.

Fig. 3 is for furnaces above 24 tons' capacity: three-phase current, each phase maintained entirely separate from the others, with each end of each phase terminating in an electrode above the bath.

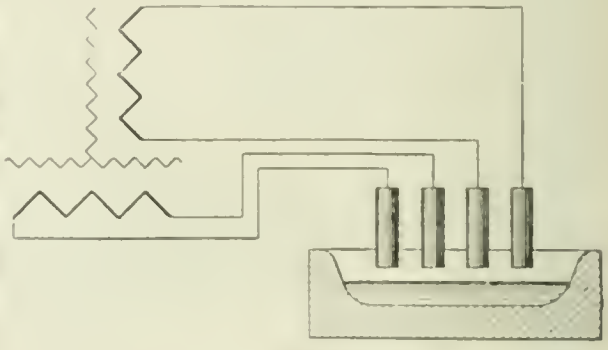


Fig. 2.

The most favourable shapes for tilting electric furnace would appear to be:—

Up to 6 tons: Rectangular in plan and in elevation with a curved bottom.

From 7 to 24 tons: Octagonal in plan.

Above 24 tons: Octagonal with lengthened back and front walls.

Stationary furnaces should always be rectangular.

The above shapes ensure the most convenient position for the electrodes in the furnace and help to keep the furnace walls at the average greatest distance from the electrodes, as illustrated in Figs. 4 to 6. It is most essential that electrodes should be in the positions shown and not opposite to doors, in order to avoid the breaking of electrodes when material is thrown into the furnaces.

A 5-ton Stobie electric steel-melting furnace is shown in Fig. 7.

Arc Phenomena.

The arc phenomena in a steel-melting electric furnace are very important and interesting. The arc proper jumps between the bath and whichever portion of the electrode is nearest to the bath. As this point is always

changing, the arc travels irregularly round and under the lower extremity of the electrode, and is seldom at more than one point of the electrode at a time. The arc proper is the source but not the only point of heating of the furnace charge. A flame of carbonaceous gas, measuring in large furnaces as much as 2 feet

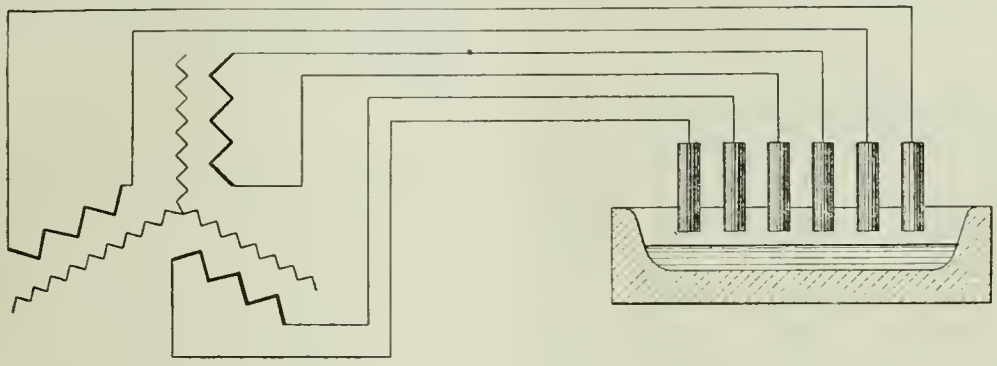


Fig. 3.

long, travels over the bath from each electrode. This flame is quite the hottest flame in commercial use and has great influence on the distribution of heat in the furnace. It is this flame which, by immediately travelling upwards in some designs of furnaces, causes therein excessively quick burning away of the roof and door arches. It will rapidly flux the banks of the furnace if allowed to impinge thereon.

Experiments were made at the Stobie Steelworks at Dunston-on-Tyne, near Newcastle, to obtain data as to the cause and effect of the direction of travel of the flame from the electrode.

Some control was obtained over the direction of the flame by alterations in the direction of rotation of the magnetic field of the supply currents. A certain change of direction of the flame resulted also from varying the phase reaching each electrode. The extent of the control over the flame was sufficient to make a

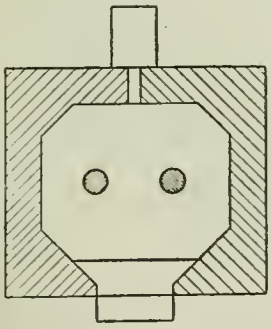


Fig. 4.

decided change in the speed of working of a furnace and in the wear and tear of the lining. Unfortunately, no definite rule for guidance can be laid down at present, as the matter further depends upon the position of the flames in relation to each other and, possibly, the magnetic fields external to the melting chamber.

Experiments on the blowing of the arc flames in furnaces by strong external continuous magnetic fields were then made in order to eliminate the uncertainty of coincidence of the revolving magnetic fields with some of the arcs in the polyphase systems of electric furnaces. Powerful lifting electromagnets were used for this purpose. Again, the many other factors existing within the arcing zones prevented any definite rule from being framed; but by a careful disposition of the electrodes and cables in an installation so as to cause the magnetic fields coincident with certain arcs to blow the arcs in a desired direction, a most important increase in speed of melting and reduction in wear and tear of furnace lining are undoubtedly obtained.

In some types of electric furnaces arcs are maintained between adjacent electrodes and not between electrodes and bath. In such furnaces the property of inter-repulsion of arc flames is utilized in order to fan the flames over the material to be melted, whilst much

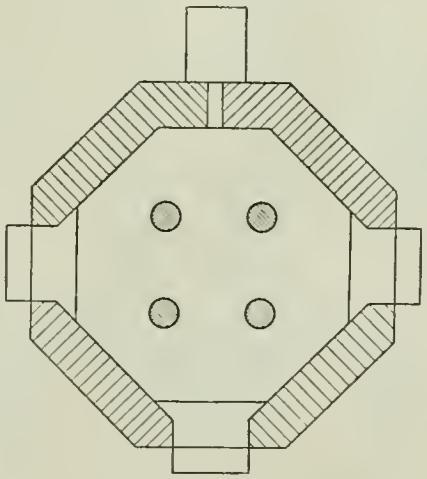


Fig. 5.

of the heat energy in the circuit, viz. that in the arcs proper, travels only between the electrodes. This is the cause of the current consumed per ton of steel melted being high in such furnaces.

It was once believed that the great heat (*circa* 3,600° C.) of the arcs in an electric furnace would have a detrimental effect on the steel. More recent ex-

perience teaches us that, so long as a steel is thoroughly deoxidized before casting, only the temperature of casting is of moment.

Transformers

One might, with reason, say that the heart of the electrical equipment of an electric furnace installation

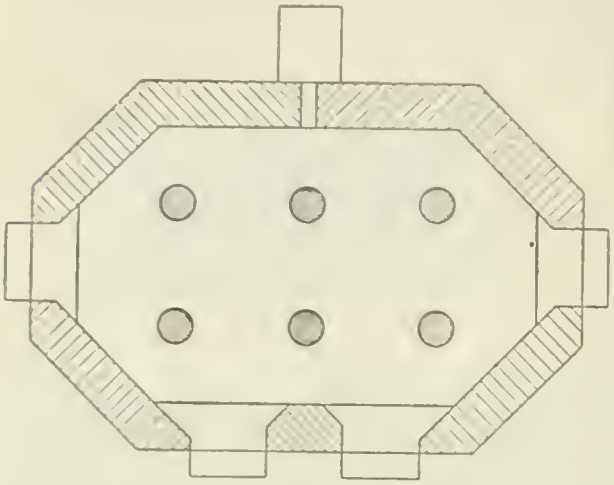


Fig. 6.

is the transforming apparatus. Either through poor construction or short capacity a considerable number of transformers attached to early furnaces gave trouble.

The stresses which the transformers have to resist are of an exceedingly heavy order. The plant has to withstand occasional short-circuiting through the furnace and, perhaps once or more in its life, the equivalent of almost a dead short-circuit. It has to allow frequent breaking of the circuits under heavy overload and, should the furnace hands be careless and the plant be unprovided with proper protective devices, of occasional switching direct on to overload.

The requirements in the design of the transformers are :—

(1) That the current density of both the low-tension and extra-high-tension windings shall be low enough to prevent the inevitable overloads from unduly heating up and deteriorating the insulation.
(2) The ventilating channels in the windings must be specially well considered so as to provide low resistance paths for the cooling oil without excessive magnetic leakage.
(3) That windings shall be braced on all sides.
(4) The low-tension windings shall be taped with such material as empire tape, in addition to press-spahn or similar stiff insulation.
(5) All clamps, no matter how small they may be, should be anchored to the transformer framework.
(6) The whole of the apparatus must be as unyielding to magnetic stresses as mechanical skill can make it.

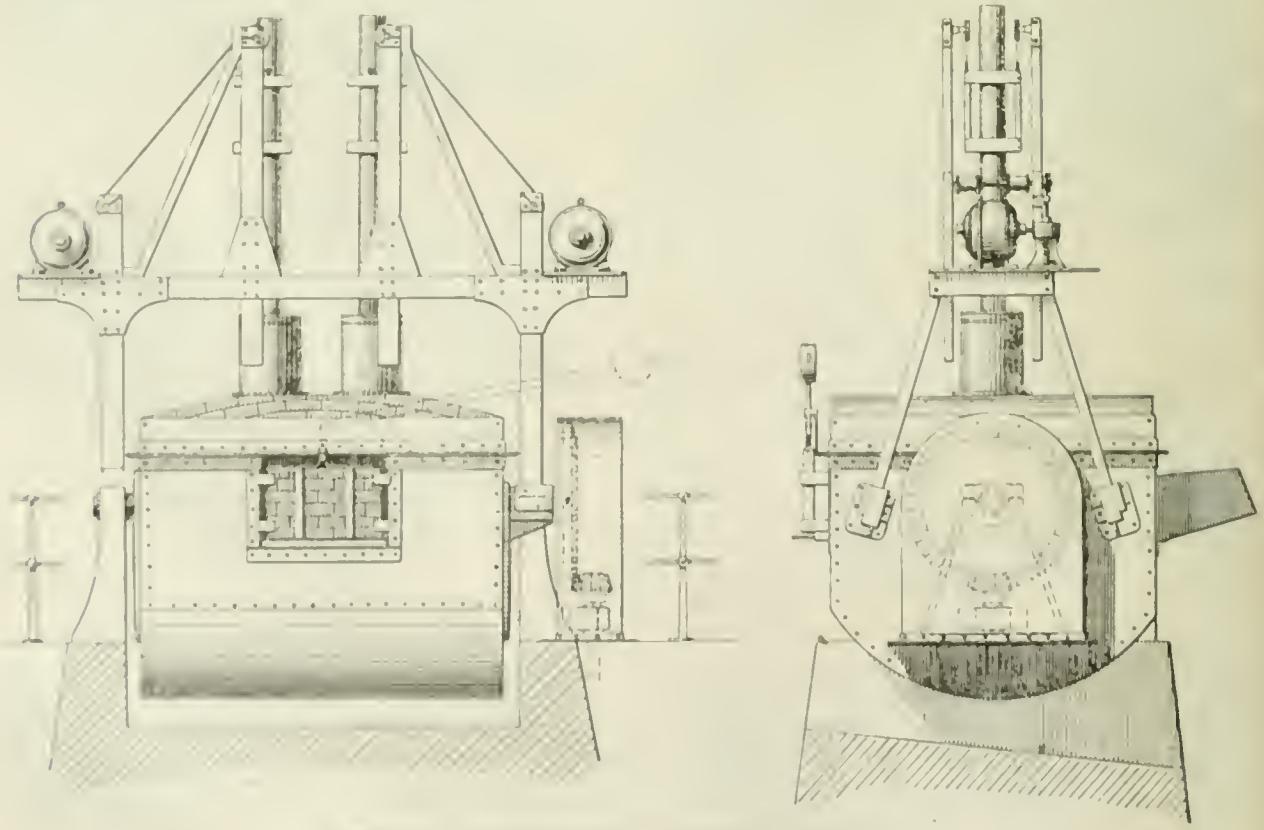


Fig. 7.—5-ton Stobie furnace, mounted on trunnions.

(7) As much as possible of the total reactance required in the whole of the furnace installation should be incorporated in the transformers.

A very few years ago furnace transformers were built upon very different lines from the above. In the year 1915 the author first specified the taping of the low-tension winding of furnace transformers and the anchoring of all clamps, the reason for these requests being that several transformers had broken down through the meeting of two lengths of low-tension copper above the windings, and that the shrinkage of wood composing parts of clamps allowed several clamps to fall and the tightening bolts had narrowly escaped short-circuiting the low-tension windings. The above practice has now become general for furnace transformers.

As a result of observations of the breakdown of some furnace transformers, the bracing of all sides of the windings of transformers was specified by the author in 1917, and a shell type of transformer embodying that feature was designed in collaboration with a well-known transformer firm. The design has now been standardized also for large power transformers.

It is usual to have several tappings brought out from the high-tension windings of furnace transformers, as the voltage required on a furnace during melting is always higher than when finishing a heat. All such tappings should be brought away from the central portions of the winding, the complete high-tension winding being divided into two at the mid-point and the tappings bridged across the mid-point to cut out equal portions of each half of the windings when required. By taking the tappings out in this way, the insulation of the end turns of the high-tension windings can be suitably reinforced to withstand any abnormal voltage stress on switching in the transformers.

On the practical side, useful results have been obtained at the Stobie Steelworks by limiting the current density in transformer windings to 1,250 amperes per square inch, the induction in the iron to about 12,000 C.G.S. lines, and the temperature rise on continuous full-load to 45 degrees C., measured by the increase in resistance. In addition to pressure-testing at twice the working voltage, an over-potential test at this double voltage is made on the high-tension side, the periodicity being increased to keep down the magnetizing current. The low-tension windings of large furnace transformers should be tested at a potential several times greater than normal by being connected in series, the low-tension coils almost invariably being designed for parallel working.

Automatic Electrode Regulators.

A few observations on automatic electrode regulators from the furnace user's point of view may be useful. The desiderata in automatic regulation mechanism include sensitiveness without fragility, and simple setting to limits. If the furnace circuits contain two arcs in series, it is necessary that the energy in each such two arcs should be balanced, whatever current is flowing. This is accomplished in Stobie electric furnaces by operating one electrode motor by an automatic current controller and the other by an automatic potential controller. The current controller is adjusted to give the limits of current required and will keep its electrode at any position at which such desired current will flow. The potential controller is adjusted so that half the available phase voltage, i.e. the normal voltage between one electrode and the furnace charge, is maintained on the electrode it controls. The result is that the potential-regulating motor will keep its electrode at the same distance from the molten steel as the current-regulating motor keeps the other electrode, as at that distance the current will be normal and the voltage balanced.

On some electric furnaces which the author is building for other steelworks the balancing of two arcs in series is automatically controlled in a different manner. The current regulator is connected to one electrode as in the previous system, whilst the potential regulator connected to the other electrode is operated as follows:—

A shunt from each electrode to the bath is passed through separate solenoids placed side by side. An armature in the shape of a bar suspended by the middle hangs over the two solenoids. When the pull of one solenoid exceeds that of the other, one end of the bar is pulled down on to contacts which operate, through contactor switches, the electrode motor in one direction. When the voltage is greater on the other solenoid, the other end of the lever is pulled down by that solenoid and the electrode motor is operated in the opposite direction.

Power Factor.

The power factor of an electric furnace installation depends upon the circuit reactances and the power factor of the arc.

The power factor of alternating arcs varies from almost unity to lower than 0·7 in the case of arcs between cold hard metals. In electric furnaces the power factor of the arcs will vary with the steadiness of the arcs and the materials forming the arcing points. As is known, the apparent resistance of an arc varies with the current passing through it, being high for a low current. The voltage wave consequently is distorted and forms a sharp peak at the commencement and end of each half cycle, with a strongly marked depression between. The current wave approximately retains its sine shape, and a lagging power factor results without any phase displacement.

The circuit reactances are divided between the transformers and the leads. Due to the large sizes of conductors used, and to the large area enclosed by the circuits, reactance in furnace work has a tendency to be very high, unless strictly controlled. At the same time, very low reactance would be undesirable on large power systems in view of the frequent short-circuits through the furnace. The total impedance on short-circuiting through a cold charge in a furnace depends very much on the type and condition of the scrap being melted, and will usually be quite high enough to reduce all shocks to reasonable limits. If, however, a short-circuit takes place through a molten steel bath, the impedance will be relatively low on account of the

good conductivity of the bath, unless a reasonable amount of reactance is incorporated in the circuits. Such short-circuits are, fortunately, very rare in well-designed furnaces.

The total impedance voltage at the moment of starting a large furnace with poor scrap sometimes reaches over 90 per cent. With average scrap it ranges between 40 and 60 per cent. When melting armour scrap or other clean heavy material it little exceeds the reactance.

A 15-ton Stobie furnace gives the following power factors:—

On melting	0·84
When charge is half melted	0·85
When charge is almost melted	0·87
When charge is melted	0·93

The average (in relation to the magnitude of the load) power factor over the total of units consumed at the Stobie Steel Company's works, including all motors for fitting shop, cranes, furnace auxiliaries and the furnaces themselves, varies between 0·86 and 0·88. The furnace load is about 90 per cent of the total load, and the balance is taken by intermittent lightly-loaded low-power-factor motor circuits. It can therefore be safely stated that large furnaces such as the 10-ton, 15-ton, and 20-ton Stobie furnaces give an average power factor of fully 0·88 over all units consumed.

The author has heard it stated at various times that one or other particular design of furnace can be worked safely at almost unity power factor. Sooner or later one hears of the collapse of some part of such gear due almost certainly to serious current surges. Considerable experience in the designing and operating of electric furnaces teaches one to aim for safety before unnecessarily high electrical performance, and this rules out of consideration furnace installations with less than 20 per cent impedance voltage when short-circuited across the electrode terminals. The author aims at installing plant in such a manner that on dead short-circuit the power factor is momentarily reduced to 0·4 or even 0·3. This need not mitigate against the excellent normal power factors already mentioned.

Electrode Considerations.

The presence of electrodes in electric arc furnaces is, for the user and designer, an unfortunate necessity. The function of the electrodes is to conduct the current into the furnace and to produce an arc gap in each electrical circuit, in order to localize, as far as possible, the conversion of the current into heat at the requisite points in the furnace. The desirable characteristics of an electrode are: low resistivity, relative incombustibility, and cheapness. No material combines these qualities. The nearest approach is found in carbon, and one has the choice between amorphous and graphitic carbon electrodes. The resistivity of the amorphous variety is, roughly, three times that of the graphitic. This enables graphitic electrodes to be made of smaller diameter than amorphous ones for equal current-carrying capacity. The following table gives the comparative data of both types of electrodes, including the diameter of electrode sufficient to carry, in practice, 10,000 amperes safely:—

	Specific resistance per cm. cube	Lowest temperature of combustion	Diameter to carry 10,000 amperes
Amorphous electrode	0·00332 ohm	513°C.	20 in.
Graphite electrode..	0·00114 ,,	624°C.	12 ,,

Graphite electrodes have not, in the author's opinion, progressed among electric furnace users so well as they would have done had unsupportable claims not been made in their favour. This is a matter which would not concern this paper but for a very important point, almost invariably overlooked by designers and users of electric furnaces, which should be ever in mind when considering the engineering features of large electric furnace installations. This point is "skin effect."

The early users of graphitic electrodes obtained their experience on non-ferrous furnaces using direct current. When such electrodes were introduced into steel-melting furnaces, which were all supplied with alternating current, it was found that the electrodes were much too hot at current densities far below the maker's recommendations. The average current density in the main current-carrying area of an electrode in an alternating-current steel furnace being roughly twice the average current density of the whole area, due to skin effect, the electrode will not usefully carry as heavy a total current as is generally claimed. This same phenomenon will attain considerable importance in other parts of large furnace plant and lead to great loss of energy and materials, unless studied in detail.

The main consumption of the electrodes in ordinary electric steel furnaces does not take place at the arcing end of the electrodes, but results from the surface burning of the carbon all over those parts of the electrodes which are inside the melting chamber and up to a point about 15 inches above the roof. On looking inside most furnaces the electrodes will be seen to be considerably tapered from where they enter the roof down to the arcing ends. Fully 75 per cent of the heavy expenditure on electrodes is wasted through this defect. Various attempts to prevent this costly waste of electrodes have been previously made, such as (1) enveloping the carbons with asbestos paste held in position by wire netting; (2) coating the electrodes with non-burning paints; (3) encircling the electrodes with steel collars held together by hinges or springs; (4) surrounding the electrodes with water-cooled cylinders extending well inside the furnace. All such methods have met with failure because, by the first method, the asbestos perishes quickly inside the melting chamber and is expensive to apply; in (2) the non-burning coatings all expand and fall away from the non-expanding carbon electrode; in (3) the collars do not protect red hot electrodes from the air above the roof; the collars are not efficient in keeping back

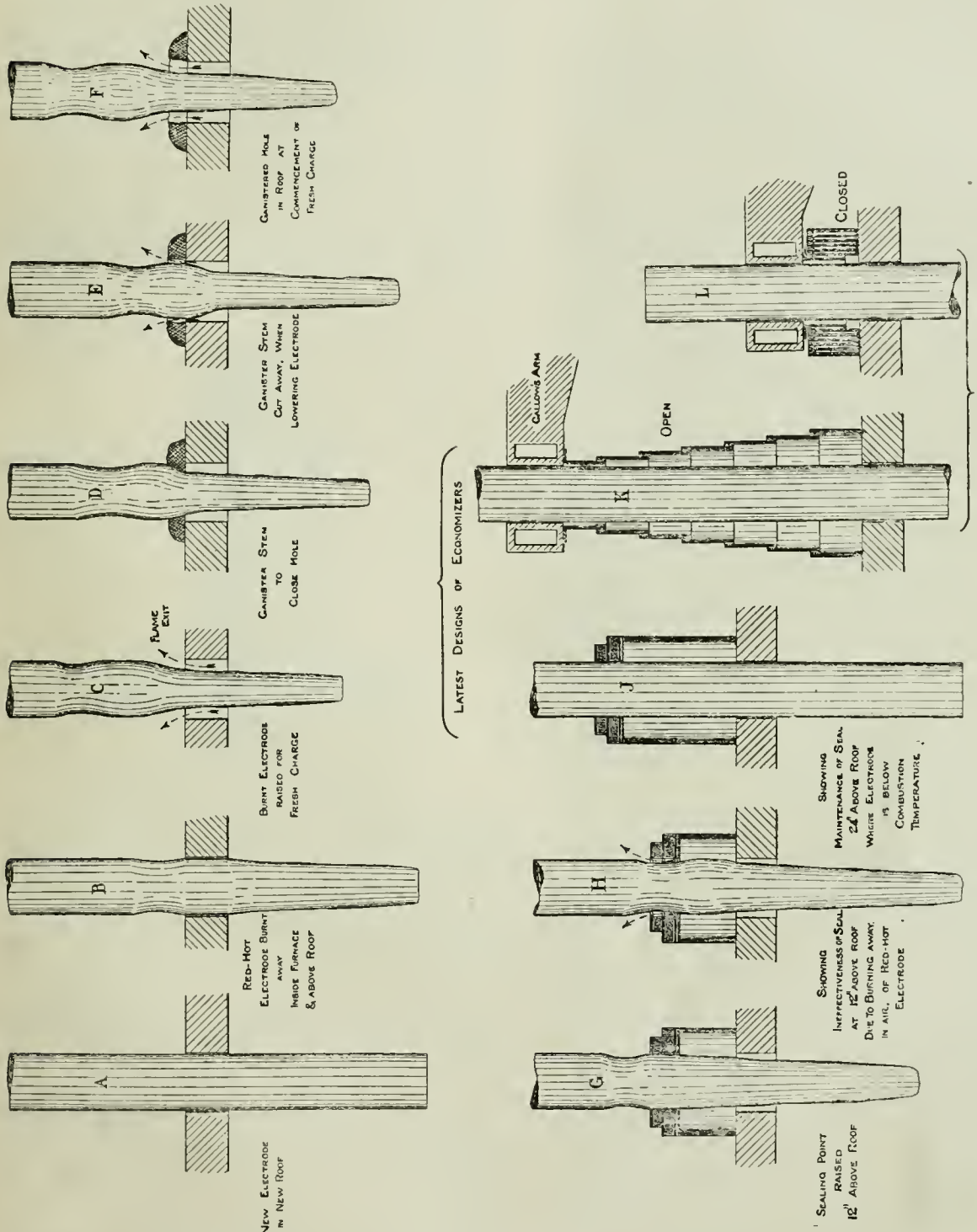

A
New Electrode in New Roof
B
Red-Hot Electrode Burnt away Inside Furnace & Above Roof
C
Flame Exit
Burnt Electrode Raised for Fresh Charge
D
Canister Stem to Close Hole
E
Canister Stem Cut Away, When Lowering Electrode
F
Canistered Hole in Roof at Commencement of Fresh Charge
Latest Designs of Economizers
G
Sealing Point Raised 12" Above Roof
H
Showing Ineffectiveness of Seal at 12" Above Roof Due to Burning Away in Air, of Red-Hot Electrode
J
Showing Maintenance of Seal 24" Above Roof Where Electrode is Below Combustion Temperature
K
Gallows Arm
Open
L
Closed
Telescopic Electrode for Gallows Arm Electrode Holder

FIG. 8.—Effect of Stobie economizers, compared with ordinary methods of sealing continuously-fed electrodes in electric steel-melting furnaces.

the flames but have a very short life and are expensive in upkeep; and in (4) the internal jackets are most wasteful of heat and, further, are dangerous inside the furnace and very ineffective.

It is thought by some people not acquainted with electric furnace practice that there is always a reducing atmosphere inside electric furnaces of the older types in use. This is an utterly mistaken notion, which is proved by the ease with which the raw materials charged into such furnaces oxidize, even without the help of iron ore or other solid oxidant.

The cause of the oxidizing atmosphere inside the older electric furnaces is the crude method of feeding the electrodes into the melting chamber. This is usually done by leaving in the roof a number of plain holes equal to the number of electrodes which have to be continuously fed into the furnace; the bricks forming such holes support annular water jackets which fit, with a small clearance, new electrodes. The heated gases inside the furnace continuously pass up those clearances between the roof and the electrodes. The results are manifold: it causes the clearance to be rapidly increased by the flames burning away the electrodes to a tapered point as previously explained; it wastes all the heat value of the gases and flames which are constantly pouring out of the furnace through the electrode holes; it lengthens the duration of a charge in proportion to the heat lost through the roof holes, the escaping flames cause the electrode gear and current conductors over the roof to deteriorate rapidly; and the undue heating of the electrode terminals necessitates their being water cooled. The considerable effect of all this on the cost of producing the steel, quite apart from some loss of control therefrom over the operations of the furnace, will be readily apparent.

At first sight it may seem a simple matter to close up the clearance between the roof of a furnace and the electrodes passing through it; but the following will illustrate some of the difficulties.

It has often been attempted to make the water coolers round the holes a sliding fit on the electrodes. To enable this to be done the electrode must be machined to size, a most expensive detail when amorphous electrodes are used. When the machined electrodes are placed in position the parts which are inside the melting chamber become white hot. Every time an electrode is raised—a constant operation in electric steel melting—some white hot or bright red hot part of the electrode is raised into the air above the furnace roof and burns away at the surface to a small or great extent. Each such reduction in diameter of the electrode commences to increase the clearance between the water jacket and the electrode, thus only delaying for a few hours the state of affairs existing in furnaces which start with the usual large clearance round the electrode.

The difficulty has now been successfully overcome in a simple way. Observations showed that at about 2 feet above the roof in most furnaces the electrodes, even when raised for charging, are seldom at a temperature at which they can burn; therefore, that is the only point at which a permanently good seal can be made round the electrodes. If an electrode is closed hermetically from the roof up to that point, the burning away of the electrode and the escaping of the heated gases from the furnace are prevented.

In practice, a light metal cylinder a few inches larger in diameter than the electrode and about 2 feet in length is fixed on the roof round each electrode. The top end of the jacket is covered with a sealing plate which prevents the passage of the flames, the electrode passing through a neatly fitting hole in the centre of such cover. Fig. 8 illustrates the effect of the apparatus.

In this figure A shows a new electrode when first placed in an electric furnace.

B shows the effect when the electrode has been in use for a few hours. The surface inside the furnace is burnt away by the internal atmosphere and, as the electrode is red hot above the roof, the electrode also burns away there in the free air.

C shows the effect of raising the electrode for melting a fresh charge. That part of the electrode where the surface has been burnt away inside the furnace has to be raised partly above the roof. This results in an immediate extension of the clearance between the electrode and the electrode hole in the roof. The result is that the flames rush out of the furnace through the roof and rapidly burn away the electrode.

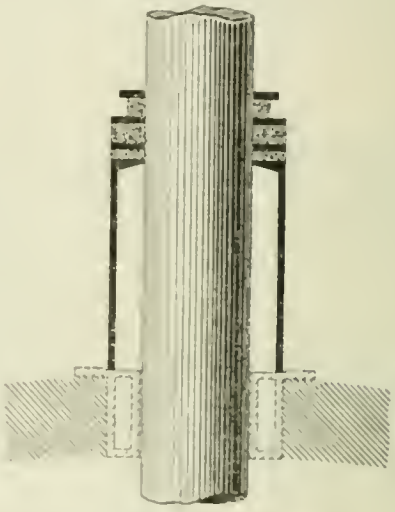


FIG. 9.—Stobie electrode economizer.

D illustrates the usual way of sealing the electrodes. Ganister or similar material is thrown against the electrode to seal up the clearance in the electrode hole.

E shows how the ganister stem is cut away by the electrode when the latter is again lowered.

F shows the uselessness of the ganister stemming immediately the electrode is again raised, due to the thick part of the electrode having created almost as much clearance between the electrode and the ganister as there was between the electrode and the original roof hole.

G illustrates the earliest attempt the author made to remove the sealing of the electrode away from the roof. This was not successful because of the still red hot electrode above the roof burning away in the air.

H illustrates the result of the above short economizer.

From this drawing will be appreciated the very small advance that this or any other short seal constitutes over the early methods of sealing.

J (Fig. 8) and Fig. 9 show the present-day economizer which forms the subject of letters patent. It is only by removing the electrode seal to a position well above the roof where the electrode is always below combustion temperature that the effectiveness of the present scheme is obtained.

K and L show the same principle of economizer in telescopic form suitable for furnaces having only a short electrode travel. The conditions that exist in an electric steel furnace are even more onerous than an inspection of these drawings would lead one to assume. The reason for this is that electrodes are not raised only when a fresh charge is put into the furnace, but they are being raised or lowered constantly for the ordinary regulation of the current on the furnace. The effect of this necessary regulation is that the electrodes are moved an average of once each 5 to 10 seconds during the first third of the process, an average of every half minute during the second third, and an average of every minute during the last portion of the process.

This most important advance in electric furnaces gives results much beyond what might be expected from so simple a device, several of the improvements being as follows :—

(1) No cold air is drawn into the furnace.

(2) No flames or highly heated air burn away the electrodes above the roof.

(3) A really reducing, carbon-depositing (when desired), atmosphere is maintained within the melting chamber.

(4) The oxygen-free atmosphere of the furnace prevents the burning of the electrodes inside the furnace except at the arcing ends and, therefore, electrodes remain parallel instead of tapering.

(5) The electrodes can be of smaller diameter for a given current supply. This, in addition to cutting down electrode costs, permits a reduction in the size of the electrode holes in the roof, thereby adding great strength to the roof.

(6) The life of the roof is considerably increased because the thick carbonaceous atmosphere inside the furnace acts as an opaque curtain through which the intense heat of the arcs cannot be radiated upwards to the roof.

(7) The flames inside the furnace, not being able to pass out at the electrode holes, travel all over and among the charge and heat this up rapidly and very economically.

(8) The electrode gear over the furnace does not become intensely hot as in older furnaces. Any adjustments required in the electrode gear over the roof can therefore be done in comfort by the furnace attendants while the furnace is at top heat. The coolness of the gear renders the frequency of such adjustments negligible. In the same way the absence of the great columns of flames, which continuously rise through the electrode holes of other furnaces and which radiate intense heat all around, renders the Stobie furnaces much cooler to work.

(9) In consequence of the exclusion of free air from the furnace, and the absolute control which this permits over oxidation, scrap steels containing oxidizable elements such as chromium, tungsten, manganese, and even vanadium, can be easily melted without losing the special elements from the bath. In other furnaces the major portion of such elements is first oxidized out of the charge into the slag and has then to be skilfully recovered, if possible, at great expense in time and current. When melting scrap which it is desired not to change at all in analysis, the carbon content does not vary by more than a point up or down. It is thus not necessary to analyse the molten bath in order to adjust the carbon and other elements when melting scrap giving the arithmetical proportions of the desired composition.

(10) The absence of heat from the electrode gear enables the current terminals of the electrode to be made of light copper contacts built up of standard copper bars, instead of the usual intricate, heavy, water-cooled bronze castings necessary in other designs.

(11) By preventing the heavy heat losses which formerly took place, the cost of manufacturing electric steel has been correspondingly reduced and the time required per heat diminished.

(12) The sealing of the roof of furnaces by means of the economizer results in the furnace being much cooler for the furnace men to operate. This and the increased output from the plant very greatly reduce labour considerations for a given output of steel. This is of great moment nowadays in view of the high cost of labour.

Circulation of Bath.

Claims are made by some furnace manufacturers that, by reason of the electrical system or the position of the current circuits in their furnaces, an automatic stirring or circulation of the molten-metal bath takes place. It is also claimed that, in consequence of such circulations, no manual rabbling of the charge is necessary.

A careful research on the subject has been carried out at the Stobie Steelworks and the results are of interest.

Many years' observation of the working of electric steel furnaces had not revealed any movements of the steel bath except such as were due to well-known causes; therefore it was decided to devise means whereby closer observation of the effects of electric circuits through molten metal could be made than was possible in a steel furnace working at temperatures up to 1,800° C. Mercury presented itself as a suitable substitute for a hot steel bath, as it resembled molten steel in being a liquid metal and magnetically inert. The resistivity of mercury at atmospheric temperature is approximately two-thirds that of molten steel. Its specific gravity is twice that of molten steel.

Separate experiments with single-, two-phase, and three-phase currents, and representing every known type of furnace with arcs playing on the bath, were made.

The size of the bath, the quantity of mercury, and the current flowing were proportioned to represent

average practice, but on a reduced scale. Two voltages were separately used for each system of connections: one low enough to enable the full current to be passed through the bath without arcs, and a higher one to pass the current through arcs above the bath as in normal steel melting.

All the different furnace systems exhibited the same effects when current was switched on.

At low voltage, with the electrodes immersed in the metal, the observed motion of the bath consisted of a very faint pulsation coincident with the periodicity of the current. The amplitude of the pulsation was greatest near each electrode and diminished with distance according to the law of inverse squares. These vibrations which originated at each electrode were so small that they were detected at the surface only by the minutely throbbing reflection of incident rays. There was no trace of a circulating or swirling motion in any part of the molten bath.

As solid conductors heavily loaded with alternating current always vibrate, it was considered that the minute waves observed in the mercury bath might originate from the vibration of the electrodes immersed therein and not from the passage of the current through the liquid metal, in consequence of the much greater area of the latter. Therefore the current was next made to flow round entirely-insulated copper circuits immersed in the bath. The same types and strength of electric current were employed as in the previous experiments. Exactly the same pulsations were noticed at the surface of the bath and a total absence of flowing motion.

The flowing movement of the slag under the arcs, visible in an electric steel furnace when the bath is covered with a fluid slag, has doubtless given rise to the common belief in a stirring of the metal bath by the current. The movement in the slag results, however, from the blowing action of the electric arcs, and it will stop immediately if the electrodes be lowered into the slag.

During the course of the above experiments it was noted that the greatest pulsating disturbance of the mercury was when the arcs played directly upon it. That disturbance was purely local and diminished considerably when a highly conducting fluid "slag" was placed on the metal. The violence of the blowing action of an alternating arc on liquid metal is observed in a commercial electric furnace if an arc is struck on to the bare steel after the removal of the slag. The steel will be blown away downwards from the electrode end and, on rebounding, will usually short-circuit the arc. The addition of a fluid slag will relieve the metal of the disturbance, as the slag will take up the blowing effort. The research conclusively proved that no circulatory or other stirring movement of the bath results from the electrode circuits in an electric arc furnace. The more or less complete diffusion of added elements which takes place in a bath of molten steel is a metallurgical phenomenon that occurs in all steel-melting furnaces, whether electric or other, and does not depend upon magnetic or convection currents. No special conditions exist in any electric arc furnace which will relieve the good steel melter from the necessity of properly rabbling his furnace bath.

Discussion at a Joint Meeting of The Institution and the Iron and Steel Institute, 8 May, 1919.

After some introductory remarks by **Mr. E. Schneider** (President of the Iron and Steel Institute) and **Mr. C. H. Wordingham, C.B.E.** (President of the Institution),

Mr. F. W. Harbord: So far as steel manufacture is concerned the electric furnace is used either for refining molten metal from an open-hearth or Bessemer converter, or for the production of steel from cold scrap. All the furnaces are very similar, and from a metallurgical point of view there is very little to choose between them; in so far as they vary, whatever small advantages some might have are in the form of the tilting arrangements and other mechanical details. The real differences which exist are in the electrical connections, and I do not feel in a position to express any definite opinion as to which is the best of the various arrangements described in the papers, as they all have certain advantages and disadvantages. During the war a very large number of electrical furnaces of different types have been erected, and one result is that the induction furnace has not been able to hold its own. So far as I am aware, practically all the furnaces which have been erected during the war have been of the electrode type. The disadvantage of the electrode type is that the electrodes weaken the roof of the furnace very much and take up a considerable amount of space in the hearth of the furnace, and what is required is a furnace so designed that it will be as efficient electrically as the electrode furnace but without carbon electrodes. If that problem can be solved it will be a very great benefit to steel manufacturers and greatly increase the usefulness of electric furnaces. The refining of open-hearth steel and especially Bessemer steel in the electric furnace has made little progress in this country, but was largely done in Germany before the war and also in America. Bessemer steel is liable to be somewhat over-oxidized, but if after it is practically finished it is poured into an electric furnace and kept there for about 1½ hours, it is largely de-oxidized and impurities remaining considerably removed; the gases have time to escape, and experience shows that the product obtained is equal to the high-class open-hearth steel. Whether it would be better to put down open hearth furnaces, or whether it would be better to have a combination of Bessemer plant with the electric furnaces in any given case would depend partly on metallurgical, but largely on economic considerations, such as cost of current and pig iron, quality of product required, etc. Another question raised in the papers is the direct reduction of ores by the electric furnace. The ore reduction furnace is a sort of blast furnace heated electrically, and theoretically it has many advantages,

but practically it has not proved to be either as efficient or economical as was anticipated some years ago. I have seen a number of these furnaces during the last 10 years and, although a certain amount of progress has been made since they were first tried, the fact must be faced that the output is still extremely small. Under conditions where the problem is to make an extremely pure iron equivalent to the best Swedish charcoal iron, and where there is very cheap power, the electric blast furnace may compete with the charcoal furnace, but the charcoal furnace produces only about 150 tons a week, whereas the modern blast furnace, working on coke, will produce anything from 1,000 up to 3,000 tons. As a competitor of the modern blast furnace producing ordinary commercial iron such as is used all over the world to-day, at present there seems no possibility of the electric furnace being able to hold its own.

Dr. J. E. Stead: With regard to the Bessemer process combined with electric refining, it seems to me that with pig metal of such very high value as it has now become—and likely to be maintained—the Bessemer process is doomed for ever. If Mr. Cooper, of Middlesbrough, were present, he could mention that his firm is entirely abandoning the Bessemer plant and replacing it with open-hearth furnaces. The advantages of the electric furnace in the duplex processes is, however, not confined to Bessemer steel, but more extensively to open-hearth steel. It is perfectly well known that in the ordinary processes of making basic open-hearth steel there is a certain amount of sulphur and phosphorus left in the finished metal, and by transferring it into the electric furnace and oxidizing it, much of the phosphorus is eliminated; and after removing the slag and adding lime the greater part of the sulphur is removed and very pure steel is in this way produced. That is the direction in which we in Middlesbrough, at any rate, and in places where basic steel is being melted, expect to move in the future.

Mr. A. G. Ellis: These papers are valuable as a comprehensive record of progress in electric furnace work in England. I do not remember having seen such a complete record since the article on "Electric Steel," by Dr. Guggenheim in the *Elektrotechnische Zeitschrift* of the 14th May, 1914. In that article, the total production of electric steel for the year 1912 is given as 135,000 tons for France, Germany, Austria-Hungary and America. The fact that this country is not mentioned emphasizes the progress made in this short number of years, as is recorded in the tables in Mr. Mercer's paper. The capacity of an electric furnace is limited by the voltage, current, and number of phases. So far as transformers are concerned, there is practically no limit to the size of transformer which can be constructed, as is pointed out in a recent paper on "Large Power Transformers" in which I collaborated.* I presume that the cost of producing steel electrically decreases with the capacity of the furnace, and I should like to hear from the authors of these papers to what extent this is so. Mr. Bibby has done a considerable amount of work in increasing the capacity of steel furnaces by increasing the number of phases. For a given range of voltage, the other limiting factor is the current, which is practically fixed by the maximum size of electrode which can be obtained and satisfactorily operated. In his paper Mr. Mercer mentions a maximum current of 11,000 amperes for a 12-inch graphite electrode. I should like to hear from the authors in their replies whether this will not be improved upon, and also what they consider to be the maximum current with which they expect to be able to deal. So far as transformers are concerned, these can be designed and built for currents up to 50,000 amperes, so that it may be anticipated that transformers will be obtainable which will be capable of fulfilling any of the requirements of electric furnaces. As an engineer who is responsible for the design and construction of transformer equipment for electric furnaces, I wish to make a few remarks on this side of the question. With regard to Mr. Stobie's remarks on transformers (page 270), I agree with him that particular attention should be paid to making a sound job of the transformers both electrically and constructionally. Mr. Stobie refers to the transformer as "the heart of the electrical equipment of an electric furnace installation"; this is certainly true, but the same amount of consideration should be given to the switchgear and voltage-regulating gear as this is often liable to be a seat of trouble, especially where a large number of tappings or complicated connections are involved. I agree with Mr. Stobie's general requirements regarding transformers, but I suggest that the question of designing transformers to meet the severe conditions of furnace operation would be more easily met if furnace builders and users would place more definite information of their operating requirements at the disposal of the manufacturers, rather than that operators should endeavour to specify details of design to manufacturers with anything up to a quarter of a century's experience in transformer design and manufacture. Trouble experienced due to short capacity of transformers attached to early furnaces has not been due to lack of liberality in the transformer designs, but more to lack of knowledge of the actual capacity required for the furnaces which the transformers were called upon to feed. It appears to me that the capacity of the earlier furnaces was determined by a process of trial and error, consisting in building a furnace and running it up to its maximum output, often throwing heavy continuous overloads on the electrical equipment. In view of the information collected in the tables of Mr. Mercer's paper, it should be possible to determine with a fair degree of accuracy the rated kilovolt-amperes for furnaces of various capacities in tons. If the furnace makers would get their information on this side of the question in order and determine the maximum continuous rating of the transformer on the British Standard basis, and adopt this as uniform practice, a good deal more uniformity and certainty could be achieved than by specifying current densities in the winding at some fictitious nominal rating. The figure of 1,250 amperes per square inch given in Mr. Stobie's paper indicates nothing unless the maximum continuous overload be specified; as a matter of fact, maximum current densities up to double this value can quite safely be employed if proper atten-

* *Journal I.E.E.*, 1919, vol. 57, p. 547.

tion is given to cooling the windings scientifically. On this point, while liberal ducts offering low resistance to the flow of oil are commendable, these are of little use if, at the same time, the width of the coils is not kept within a low limit so that the heat can be readily transmitted from the centre of the windings to the oil ducts. Regarding the question of coil bracing, there is no doubt that this is of considerable importance in furnace transformers owing to the rapidly varying load and shocks due to short-circuits through the furnace at the melting period. When comparing this service with that of ordinary power transformers on large systems, the following points should, however, be borne in mind:—The total reactance of a furnace transformer, low-tension leads and furnace, is very high. During the melting period, it may be as high as 70 to 80 per cent, and during the refining period, 40 per cent of the normal voltage. Under these conditions the current in the transformer, even with a dead short-circuit through the furnace, is only of the order 1·25 and 2·5 times full-load current respectively. In an ordinary power transformer, the total reactance should be about 6 per cent, corresponding to a short-circuit current of about 17 times full-load current. Since the stresses on the windings vary with the square of the current, it is evident that furnace transformers on account of their inherent high reactance are subjected to relatively much lower stresses than transformers on power systems, although the stresses in a furnace transformer are continually varying with the fluctuating load. In considering the statement in par. 3, page 270, that "the windings shall be braced on all sides," the qualification is necessary that the design of the windings should be examined with a view to ascertaining the possible directions in which the coils tend to move by magnetic interaction. This can be done easily by remembering the general rule that conductors carrying current in the same direction will attract, and conductors carrying current in opposite directions will repel, one another. The coil heads on a sandwich winding, such as is usually employed for furnace transformers, are normally not subject to any magnetic stresses tending to move them radially outwards, but only axially, in which latter direction they are always effectively braced. Cases of radial displacement of windings have been met due to internal short-circuits in the coils where tappings are brought out—always, to a certain extent, a weak point in the winding. Under such conditions, the magnetic repulsion is due to a sudden reversal of current due to a short-circuit on part of the windings, and no elaborate system of coil bracing will protect a transformer against this trouble. The addition of numerous clamps on parts of the coils in directions where there is no tendency to move is only adding unnecessary expense and complication to the construction of the transformer, which it is essential should be kept as simple as possible. This question is dealt with at some length in the paper already mentioned on "Large Power Transformers." I should like to point out that hundreds of thousands of kilovolt-amperes of power transformers have been built and operated for many years without resort to fancy complicated devices for bracing the windings. In England the usual construction employed for furnace transformers is the single-phase shell type; in such, the windings except the coils heads are naturally anchored in the core punchings by which they are enclosed. It is worthy of remark, however, that numbers of core-type furnace transformers have been built on the Continent with coil bracing such as is normally employed on similar large power transformers. Referring to par. 4, regarding the taping of the low-tension coils, this is usually unnecessary if the high-tension coils and the barriers between the high and low tension are sufficiently well insulated. The low-tension coils consist usually of deep copper strap wound on edge, which needs no special insulation. The oil coming in contact with the bare copper affords an excellent means of getting rid of the heat, and to tape such coils only impedes this process. On the question of tappings on the high-tension side for regulating the low-tension voltage, it is the usual practice to place these in the middle of the windings, the reasons being to preserve the magnetic symmetry of the two halves of the winding and to ensure that the reinforced end turns are always left in the circuit, as noted in the paper. A good deal of assistance in ensuring a reliable transformer can be rendered by the furnace makers if they can settle down to a small number of voltage tappings, since the bringing out of high-tension tappings on transformers for this class of work is actually the source of weakness. High-tension tappings are not to be recommended for line voltages above 11,000; above this voltage the regulation should be attained by means of booster transformers or induction regulators. These arrangements lead to a rather increased first cost, but this is entirely offset by the increased reliability of the installation. The use of separate voltage-regulating gear is also an advantage if the main transformers can still be run at one low tension in the event of failure of the regulating gear or tappings. Furnace installations fed from extra-high-tension systems of 30,000 volts and over are not yet called for in this country, but I have designed a number of transformers for this work. In such cases, although satisfactory furnace transformers can be built for the extra high tension, it is generally advisable to step down the line voltage to an intermediate voltage of, say, 6,000, in which circuit the regulating gear is placed.

Mr. D. F. Campbell: It may interest members to know a little about other electric furnace developments, apart from steel and iron which are mentioned in the papers. In 1914 this country was in a desperate position for supplies of tungsten, and also for ferro-chrome. There was one small works in the Newcastle district which was capable of making a very small quantity of ferro-silicon. Before the end of the week after the first telephone message had been received, ferro-chrome was being made. In 1918 the works were consuming 80 million units a year and supplying the whole of the requirements of this country in ferro-chrome, and they were also capable of making all the ferro-tungsten necessary. The extension of those works involved, amongst other things, building a house for the manufacture of ferro-tungsten, and as early as 1915 over 250 tons had been produced at a time when the country

was in an awkward position with regard to that metal. A further extension involved the laying of a 20,000-volt cable over 5½ miles long. That was done extremely rapidly, and at the time of the Armistice ferro-alloys were being made at the rate of over 10,000 tons a year, and the whole of the requirements of the country were being met. The expansion of the electric furnace industry since 1914, in steel alone, has grown to about 40 times the pre-war output, and the kilovolt-ampere capacity employed is about 100,000. In addition to that, about 50,000 k.v.a. was used for the manufacture of carbide, phosphorus and similar purposes, and, in addition, the k.v.a. capacity which was used for the manufacture of alkalies and aluminium has also to be considered. The development of alkali manufacture by means of electricity is now assuming very large proportions. Amongst other problems during the war was the lack of Swedish iron, which was very largely overcome by the electric furnace. Not only has an electric furnace substitute of Swedish iron been made for the crucible process, but also large quantities of tool steel have been made direct by the electric furnace, which is, I think, equal in all respects to the tool steel made by the crucible process, provided the same care is taken. The great difficulty experienced in the early days was to get skilled melters, and to take the same care in casting small ingots with a comparatively large amount of steel which was made in one batch in the electric furnace. The next problem which arose was that the great expansion of electric furnaces created a position of great danger as regards the electrode supplies, and that extremely difficult and intricate manufacture had to be tackled in this country. At present there is more than sufficient capacity to make the electrodes required in this country, and I hope that a very valuable export business will be developed with Scandinavia, which is extremely badly situated with regard to coal supplies and raw material for the electrodes, which are essential to the large manufacturing industries of that country. The economic position in regard to making alloys will be profoundly changed by peace conditions, and there is no question that certain industries, such as the manufacture of ferro-silicon, will not be economically possible in this country in the future. With regard to the electrical equipment of the electric furnace, certain alterations have been made and a great many new connections of transformers have been suggested during the last few years, but no very great radical alteration or improvement has been made in the efficiency of the furnaces except in details of design. I strongly agree with the last speaker that robustness of construction is most important, and especially is it important to follow as closely as possible the ordinary Siemens open-hearth practice with regard to the lining of furnaces. No great alteration has been made in general metallurgical practice. The principal problem has been the re-melting of scrap and the saving of as much chrome and nickel as possible from the turnings which were available during the war. It has been a very valuable asset to be able to save the whole of the nickel and a great part of the chrome. One electric improvement which I think has a future, is the use of high reactance at high voltage during the melting period, and a low voltage and low reactance during the finishing period. The advantage of that is that the shocks, the objection to which has been very much exaggerated in the past, are overcome and the load is steadier, so that full load can be put on to the furnace immediately. By a simple system of switches giving the furnace two voltages and two reactances, it is possible to arrive at conditions which are very favourable for melting and refining, and so maintain a steady load while melting and reduce as much as possible the cutting of the refractories in the last stages. It is interesting to note that in very large works the performance of the furnace is not so good as it is in small works. That is almost entirely due to the traffic and cranes, and things of that sort. I have the figures of one foundry, which in six months melted 1,966 tons of steel at a current consumption of 617 units, which is exceptionally good, but in that case it was a small works where crane facilities and everything were the very best for the furnace. Such good results are not obtained in large shops. There is one question which I think ought to be of interest to the electrical engineer, and that is the matter of power contracts. The consumer of electricity and the supplier of electricity have not got as close together as they might have done on this point. The service given by the Sheffield Corporation in supplying energy to electric furnaces has been remarkable, but the power contracts in Sheffield give no advantage to the man who has a high load factor as compared with a low load factor, the system being merely to charge so much a unit, minus a discount according to the number of units used. On the North-East Coast they pay so much a unit with or without a fixed charge, plus a certain amount for the increase in the price of coal above a certain fixed figure. That has the disadvantage, I think, that a good many people do not understand it, and there is a good deal of discontent in regard to the drawing up of the contracts. I should like to suggest that some system of contracts should, if possible, be arrived at which is very much simpler and which might, for instance, consist of a fixed price per unit plus or minus a sliding scale discount for a good or bad load factor, a further sliding-scale discount on large quantities and also a fair coal clause. There is one interesting instrument which has been developed during the war, for the regulation of a large number of furnaces by means of a "master regulator." If a large number of furnaces are put on one feeder, the total load on those furnaces can easily be controlled within a certain limit, and that limit can be varied at will from the power station. In that way full advantage can be taken of any load which suddenly becomes available, the peak load can be kept within the desired limit and full advantage taken of the diversity factor of the number of furnaces. It is only by improving the load factor and generally by improving the conditions of the power consumed that a substantial reduction in price can be obtained, and I think there is room for closer working between the consumer and the supplier of power.

Sir R. A. Hadfield : The chief point with regard to the application of electric energy to steel melting or producing alloy steel of a special type is the cost of

power, and I am glad to know that a Commission has been sitting for some time with a view to bringing about the establishment of large power centres from which it is hoped to get electrical energy at cheaper rates than now. If it is going to cost something like £2 5s. or £3 per ton for the energy employed in melting steel, whilst the cost to Canadian manufacturers in 10s or 12s per ton, this country will be at a very serious disadvantage. Whether this country can compete whilst Canada and other centres obtain water power so cheaply from Niagara and other important centres, I am not able to say. Bearing on this point I may mention Sir Dugald Clerk's recent important Report on Water Power. Whilst much has been done in this country, we have still to try to bring about a lower cost of electrical energy for melting steel. During the war my firm have done useful work in the manufacture of electric steel. We were able to utilize and work up something like 100,000 tons of waste material for war purposes, which otherwise could not have been utilized at all, or at any rate not to the same advantage. I have received the following interesting letter from M. Paul Girod, who has asked me to read it to the meeting :—

"Dear Sir,

"I regret that, much as I should have liked to be present at the meeting of the Iron and Steel Institute on the 8th May, I am obliged to decline. I see the programme includes an important discussion on the electric furnace. May I ask whether you will be good enough on this occasion to act as the mouthpiece of French electro-metallurgy on the one hand, and of myself on the other? In the splendid progress that has been made in the manufacture of steel in the electric furnace during the war, it is rather a pity to find that, with the exception of the Héroult furnace, all furnaces recently installed are 'new.' The merit of the few inventors certainly counts for something. The war, however, has thrown so much strain on French industries and under such different circumstances that all companies have been compelled to confine their activities and the use of their staffs to the working of their own factories. Consequently, all business connected with patent licences, interesting as they may be, has had to be shelved, not so much from the 'material' as from the 'moral' point of view. I myself have increased my output from 15,000 tons of ingots per annum to 60,000 tons—a figure which is all the more remarkable as it was obtained from furnaces working on cold charge and was devoted exclusively to the production of alloy steels for the manufacture of artillery, road vehicles, and aircraft. My works have purchased from outside all steel used in the manufacture of ordinary shell, reserving its entire productive capacity for the manufacture of steel which cannot be obtained in the Martin furnace with a sufficient degree of quality and regularity. No doubt the important development of the 'mixed' type of furnace (i.e. in which the current passes through the hearth and the electrodes) will come out at the meeting. The number of patents taken out for furnaces of this type for some years now, and especially during the last few years, is so considerable that it may perhaps not be out of place to state that, as long ago as 1899, I designed a tipping furnace having a conducting hearth (which was used for the manufacture of alloy steels), while in 1905 I patented a furnace having embedded metal poles, which, unless I am mistaken, is really the prototype of all industrial steel furnaces having a conducting hearth. If we have to concede to M. Héroult absolute priority for the manufacture of steel on an industrial scale in the series arc double-electrode furnace, I think I may claim for myself priority for the opposite principle, which consists not only in using the current at the surface of the bath, but in causing it to pass through the whole of the molten mass, and that with the longest possible passage so as to secure (1) great regularity, and (2) greater ease of manipulation of the furnace for cold charges. You will also be interested to know that we now have working at Ugine a number of furnaces of a capacity of 25 tons on cold charge, these furnaces being capable of taking 30 tons on liquid charge quite easily.

"I am, etc.,

(Signed) "Paul Girod."

M. Girod has furnished the fullest information not only to my own firm, but to a number of other makers in this country during the war. Mr. Mordey (p. 283) has referred to only 600 units of heat being employed. I should like those who are not users of furnaces to know that that is really for melting mild steel. If we are going to make steel from pig iron it will take much more than 600 units. When we started during the war we had to pay about 0·6d. a unit; it then rose to 0·7d. and it is now 0·8d., and Sheffield steel makers believe that it will soon be 1d. Metallurgists are not electrical engineers, and I hope electrical engineers will give us all possible assistance since we shall have in future the competition of the world to face. In America electrical energy is being applied for annealing, heating, and a number of other operations, and it can be seen therefore how important it is for us to lower the cost of energy. There is another matter on which we want the help of electrical engineers. Is what we term the heat obtained from electrical energy of the same quality as that which is obtained by combustion? I am inclined to think it is not. I think there is some difference, though it is difficult to say what it is. Only a short time ago I was watching a heat of electric steel being poured, and came to the conclusion that there is some difference in the effect of the electrical energy upon the molecular construction of the steel. Can electrical engineers throw any light upon that point? Is electrical energy applied for heating purposes the same as energy obtained from combustion? I specially refer to the point because a well-known Sheffield man, Lord Chetwynd, formerly of Messrs. Vickers, brought out a process of which considerable use has been made during the war, by applying electrical energy to the head portion of the ingot after it had been poured for a considerable time, 30 or even 40 minutes, that is during the cooling of the steel. The ingots treated were of large size, 15 to 20 tons or more. He claims that by this method he gets rid of a large number of what are known as inclusions in the steel. I have examined some of those ingots at

our own works, and have not been able to see any great difference, but Lord Chetwynd claims he can get better transverse tests and better quality of product. In that case it may be that electrical energy has some effect upon the molecular structure of the material. We must not forget that above 750° all iron and steel is non-magnetic, and therefore it is not likely this could be a magnetic effect but would probably be some other effect.

Colonel D. Carnegie : I desire to refer to what has been said with regard to the design of the electric furnaces, and also to their operation. The Imperial Munitions Board in Canada was placed in a very awkward position during the war, owing to the very great quantities of turnings which had to be sent to the United States while the Board was buying steel for munition purposes from the States. It was ultimately decided that electric furnaces should be installed in Canada. Electric steel manufacture is not new to Canada, which country has had experience of several types of furnaces such as the Héroult and some other modified fixed types of electric furnaces. After considering what was likely to be the best design, the Héroult furnace of the 6-ton capacity type was selected. A row of 10 furnaces, all well above every factor of safety hitherto used, was installed, with the hope of getting from the ten 6-ton furnaces a capacity of 300 tons per day liquid steel. Five months after foundations were commenced, steel was obtained, and instead of obtaining a capacity of 300 tons per day from the 10 furnaces, approximately 400 tons were produced. I mention these facts simply because it is my experience, confirmed by actual practice, that there is no economy in installing any part of an electrical equipment unless one is sure that there is a high factor of safety on every part. Turning to the question of the cost of current, to which Sir Robert Hadfield has referred, there is no doubt that Canada has great advantages for the manufacture of cheap steel from the electric furnace, owing not only to cheap power, but also to the fact that it has magnesite in abundance. It also has facilities for the manufacture of carbon and graphite electrodes at a cheap rate. So that considering costs of production from the electric furnace, I think I am safe in saying that the best open-hearth basic steel, or even acid open-hearth steel, cannot be produced in Canada more cheaply than steel from an electric furnace using 100 per cent turnings. Coming to the question of power, one speaker has said that it is a great thing to get steel produced with a consumption of about 617 units per ton. Very likely it is on a small system, but in Canada we were consuming something like 550 to 575 units per ton of steel melted. I should like to ask the authors if it is possible to produce steel economically direct from ores by the use of the electric furnace. Experiments have been made in Canada with this object, but the results have not been very successful. I see no reason, however, why the difficulties in the production of steel direct from the ores should not be overcome. In passing, I should like to mention that, driven by the same necessity as was England, Canada utilized its electric furnaces for the production of ferro-molybdenum, ferro-titanium and, for many years, ferro-silicon. I regret to learn that it is unlikely that England will produce ferro-silicon economically. There are immense possibilities in Canada for the production of ferro-silicon, and I hope that country may have preference over Norway and Sweden when these materials are being purchased.

Mr. W. E. Burnand : Whilst there are many differences of opinion in regard to the details of the electric furnace, I think on the whole there is little question that the electric furnace has made good. It certainly seems to have made a lot of money for the users, and they do not seem to have one electric furnace very long installed before they can afford to put in another. In Fig. 2 of Mr. Bibby's paper, I do not see how the distribution of current or potential is obtained. The voltage across 2 and 3, compared with that between 1 and 4, should be equal with uniform resistance round the electrodes. If there is a short-circuit or a low-resistance between 2 and 3, say, that will reduce the voltage across those two, and increase it across 1 and 4. That will give increased heating across 1 and 4 where the high potential is, and reduced heating across 2 and 3. If the transformer windings are star connected as indicated in Fig. 4, the effect is that if one gets a short-circuit or lower resistance between 2 and 3, a bigger current will flow, and consequently a bigger heating with the lower resistance, provided the external reactance is not high. Therefore, with a properly proportioned high reactance, one may get a more uniform heating under those conditions, due to the reactance lowering the voltage sufficiently to compensate for the increased currents. Fig. 7 in the same paper seems to be a very complicated arrangement for getting 8 phases. There is no difficulty in getting 8 phases on one transformer with three legs, or from two single-phase units properly coupled up, so that I do not see why one should go to the expense and complication of five transformers to accomplish probably the same result. Referring to page 251 of Mr. Greaves's paper, it seems to me that the current does not balance on the primary or even on the secondary at starting, and that even to get balanced current when working the voltage would have to vary with the varying resistance of the furnace. At the same time I do not think the out-of-balance current, which I presume does occur, would be a serious matter, especially in view of Professor Miles Walker's recent demonstration* that 20 per cent of the generating capacity can be taken off one phase without any serious unbalancing of the supply pressure. 20 per cent is a big proportion, and more than is obtained in any single furnace in the ordinary way, so quite a considerable amount of unbalancing is permissible even at the present time, and the amount will increase as the size of the generating unit increases. I think both Mr. Greaves and Mr. Bibby mentioned that they have measured the heating from the bottom electrode ; I should like to know how it was measured, and what figures were obtained. There is one other matter : should the reactance be internal to the transformer or external ? On the whole I think the external arrangement is preferable. If one obtains increased reactance by not sandwiching the primary and secondary coils

* *Journal I.E.E.*, 1919, vol. 57, p. 109.

one certainly limits the current on short-circuit, but one also increases the forces acting between the coils, so that there is not a very great difference in that respect.* Also, the leakage flux round those coils tends to heat up both the case and the iron. A simple way of getting that increased reactance is by threading U-shaped stampings on the secondary leads. Any reactance required can be obtained in that way and it seems to me simpler as well as cheaper than to put it in the transformer; one also obtains the advantage that it can be varied as required. On large sizes I think one gets from the secondary leads themselves more reactance than is wanted apart from any in the transformer,† so that as these sizes increase it is necessary to keep the reactance down to the minimum in the transformer, and the leads from the transformer to the furnace must be interleaved‡ in order to reduce the reactance.

Mr. A. Hutchinson: In connection with the use of the electric furnace to produce a finer quality of steel in the open-hearth process, Sir Robert Hadfield mentioned the cost of current. I think that in modern blast furnaces and steel plants connected with coke ovens it is possible to obtain current cheaply from gas-engine plant using the waste gases from blast furnaces and coke ovens.

Mr. Walter Dixon: I have been wondering what, in particular as a result of the discussion, this meeting is trying to settle. Nothing of particular moment appears so far to have resulted. One statement has been made which appears to be useful, viz. the induction furnace is out of the running. Another point is that the differences between the various types of furnaces are more or less matters of detail. Might I suggest that some of the steelmakers should state what practical results they have obtained compared with the theoretical results put forward and claimed in the papers. Speaking generally, I believe it is the war (when economies have been a minor consideration) which has brought this question of electric furnaces into prominence. In other words, the increase in electric furnaces in this country is due mainly to the fact that they have offered special facilities for dealing with special materials. To imagine, as some have done, that electric furnaces are on the way to compete with and replace blast furnaces is as wide of the mark as it is to imagine that they will ever replace open-hearth steel melting furnaces. Electric furnaces with a capacity up to, say, 10 tons for dealing with special classes of materials are a sane and sometimes—though not always—an economical proposition. If the price of fuel continues to rise, and the price of electricity, as some appear to imagine, continues to fall, then their scope will be increased. But if, and when, this condition arises, it will have to be remembered that the system at present adopted in electric furnaces puts electricity under one of the worst possible conditions, largely inconsistent with the simplicity which has been urged as one of the present practical demands.

Mr. E. H. Saniter: I have only had a small experience in the making of electric steel, but I am strongly of opinion that for ordinary competitive work in what might be called structural steels, and even finer steels than that, the electric furnace has not got the slightest chance. I am also of opinion that for many of the finer steels the acid open-hearth furnace can do equally well and at much less cost; that is assuming, of course, present conditions. If electric current could be obtained at a very much cheaper rate, and if electrodes could be got which would not be continually falling into the bath, the electric furnace might do a good deal better. As far as I have been able to test electric steel against similar steels made in the acid open-hearth furnace, I have not been able to find that electric steel is in any way superior. I hope that with further experience and with improvement in the furnaces the extra cost may be justified. I certainly think that for certain classes of what might be called tool steels there is a considerable future for the electric furnace. In this direction the size of the electric furnace is an important factor.

Mr. E. Adamson: For the manufacture of iron and steel there are two kinds of furnaces used, one for steel refining and the other for pig-iron smelting. The arc furnace is described in the papers as the one used for the production of steel, but so far it has not by itself, or in conjunction with other methods of making steel, shown that it can compete with the Siemens furnace for structural steels. Electrically-produced steel has its users, but so far they are comparatively small in number and are limited by reason of the cost of production, and it has not yet been proved that electric steel produced from common scrap, such as burnt iron, is equal to that produced from the better classes of raw materials. The deciding factor in regard to the use of electric furnaces is naturally the cost of current, and this country cannot produce current as cheaply as some of the water-power installations in Europe and America. The nearest approach to this is when the power is produced from the waste heat, which is either not charged for or only charged at a nominal figure. I have been interested in electrically produced pig iron, and have come to the conclusion that the cost of power and the geographical position of the works in regard to ore and fuel are still deciding factors in regard to the position for electric blast furnaces. In some countries where the works are close to the ore, the cost of power to the furnaces is almost as low as 3*s.* per electrical horse power year. The question of ferro-alloys is one to itself, as the geographical position of the smelting works is a most important factor, especially in these days of high freights, and considerably more should be possible in the production of these alloys in this country than has so far been done.

Mr. H. M. Ridge: I think there is one aspect of the subject which has not been touched on by any of the previous speakers, namely, that there are really three elements concerned in the design and use of the electric furnace, electrical, metallurgical and constructional. Each of these at present should be dealt with by separate experts in the particular branch. There is not only the question of the electrical engineer and the metal-

* [illegible] "Transformers," *Electrician*, 1915, [illegible].
† *Ibid.*, [illegible].
‡ *Ibid.*, [illegible].

lurgical engineer, but the constructional man is also required, and his knowledge and experience have been rather lacking in some of the electrical steel furnaces built in the country. I think that co-operation between the three would assist in rapid progress and give much improved results in addition to longer life of the plant.

Mr. H. H. Ashdown: I fully endorse Mr. Saniter's remarks with regard to the limits of the electric furnace. From what the previous speakers have said, the impression might be formed that the best steel can be obtained under any conditions from the electric furnace. That is not the case. The utmost care and attention must be given to the steel during its process of manufacture in the electric furnace if the best results are to be obtained. I have not made electric steel, but I have examined a fair amount, and I know the conditions under which it was produced. As an instance, a special charge was made from the best pig iron and selected scrap. It was made in the electric furnace by one of the most experienced makers in the country. Unfortunately that charge was anything but desirable. Had it been used for ordinary work, the defects probably might not have been noticed, but when steels are tested transversely any defects present are almost bound to be detected, and it appears to me from notes that I saw in *Engineering* last week, referring to papers before some of the American societies, that the serious defects I have detected in testing and examining electrically-made steels have been very pronounced in America. I am certain that my remarks would apply not only to some of the special steels, but also equally to the tool steels. I feel sure that there is a limit to the capacity of the furnace, and to obtain the best results the very greatest attention must be exercised. It is a mistake for anybody to think that good steel can be obtained from an electric furnace without the greatest care and attention being devoted throughout its manufacture.

Mr. W. M. Mordey: I should like to ask whether steel makers and electric furnace makers are not a little unreasonable in asking always that the price of electrical energy should be reduced. The remedy seems to be in their own hands. Nobody can watch the working of an electrical furnace without seeing evidence of great loss of energy in various directions, which if prevented or reduced would have just as much effect as a reduction in the price of electrical energy. Not long ago it was customary for makers and users of steel furnaces to admit a consumption of 1,000 units per ton, or 1,100 units, or more, for furnaces which were not working continuously. We have heard to-day from Mr. Campbell, and no doubt other makers could give similar experiences, of steel being produced for 560 and 570 units a ton, and Mr. Carnegie, who gave his Canadian experiences, claims to have got down in practice to considerably lower than that figure. Sir Robert Hadfield has spoken of the cost of energy being 50s. to 60s. per ton of steel—that means about 1,100 units per ton at ½d. a unit. There seems to be room for a lowering of the consumption or of the price in that case. Such matters are largely beyond the province of the electrical engineer. There is also an important economy to be obtained by the reduction of the consumption of electrodes. I do not know the present cost of electrodes, but when I had occasion to look into the matter not very long ago during the war I found it was anything up to 20s. per ton of steel. The making of electrodes for electric furnaces seemed likely to offer a more profitable field even than making steel, and I commend it to those who are in a position to carry it out. Wasteful escape of heated gases round the electrodes is a cause of further waste by consuming and tapering the electrodes. Mr. Stobie seemed to have tackled that part of the problem successfully by the use of his electrode economizers. The question has been asked, what is the secret of the great growth of these furnaces during the war? May I suggest the answer is in the one word, "swarf"—that is, the turnings and borings mostly from the shell factories? That material formed the principal food of most of the electrical furnaces. The experience gained in that way will no doubt be of great value now. In conclusion I should like to ask a question about the induction furnace. From the electrical point of view it has many very attractive features, and I am loath to believe that it is really dead. It would be very useful to have a paper on the difficulties which have led to its practical abandonment. It is true that it has a large hearth area for leakage of heat, but there are no hot gases to pass away, no flames, and no electrode troubles. The "pinch effect" troubles were said to be serious, but later reports suggested that use could be made of that effect. There should at least be a public post-mortem examination so that we may know more about the actual causes of the disappearance of this very interesting type of furnace.

Mr. S. S. Parker: It was my privilege in 1908 to superintend what may, I think, be described as the first commercial run on an electric furnace in the British Isles. The furnace was of the Kjellin fixed type, 30 cwt. capacity, installed at the Sheffield works of Messrs. Vickers, Ltd. The plant was designed for the purpose of melting cold charges, and to that process my remarks are chiefly confined. Although the furnace was nominally of 30 cwt. capacity, only 2,500 lb. was "tapped," the remaining 1,000 lb. being left in the furnace for the commencement of the next heat. This is necessary because in this type of furnace the melting process depends entirely on the current induced in the "bath" itself, and unless this quantity of metal is left in the furnace, the melting of a subsequent heat cannot be continued. To this fact the majority of the difficulties in working, and objections to the induction furnace can be traced. When only one class of steel is required the difficulties are not so great, as only two-thirds of every heat are transferred to the ladle. If, however, one has to make straight carbon, nickel chrome or ordinary nickel steels, when and as required, the difficulties immediately become apparent to every practical steel maker. Owing to the nickel and chromium contents of the 1,000 lb. of metal left in the furnace, it would be obviously impossible to change from nickel chrome to straight carbon unless the furnace could be completely emptied and a fresh start made. If worked in connection with any other melting process, one could easily obtain the necessary amount of metal from that source, but in a self-contained plant some auxiliary process (say an oil furnace for melting pig

iron would be most desirable. The electrical engineer may suggest the melting of steel rings, but this has been thoroughly tried and found unsatisfactory. Even when the rings are most carefully prepared to minimize segregation, and are machined to give an equal cross-sectional area, it is almost impossible to prevent them heating and melting unevenly, which renders this method worthless except as a means of drying the linings, preparatory to commencing the melting process. Unless molten metal is available for the commencement of each week's run, a portion of the Saturday's heat has to be left in the furnace and sufficient current maintained to keep this in a liquid state during the whole of the week-end. This week-end work necessitated the use of approximately 2,500 units, which, when added to the current used for the week's work, considerably increased the current consumption per ton of output. Possibly the more serious objection to leaving a portion of each heat in the furnace is that it makes proper inspection of the furnace lining impossible. This inspection is most necessary owing to the continual circulation of the molten metal which, with full power on, develops into a regular "swirl," the banking of the metal on the outer edges of the bath being quite apparent. Although later we experimented with scrap of various qualities and conditions, our first run was made on selected Swedish bar iron (3 in. × $\frac{5}{8}$ in.) cut into 9-in. lengths. All the materials used were as free from oxide as possible. During that first run we found that our losses, which we took to be oxidation, worked out at approximately 2·7 per cent. On the termination of the run, when the furnace was completely emptied for the first time, it was discovered that our losses due to oxidation were actually 2·32 per cent, and that 0·39 per cent of the apparent oxidation was actually increase of the bath, due to the gradual washing away of the lining below the lowest working level, and caused by the "swirl" mentioned above. In other words, after producing 150 tons of steel, the weight of metal left after the final heat, which should have been 10 cwt., had increased to 22 cwt., although the wear on the upper portion of the lining had been comparatively light, necessitating only slight repairs during the run. As a result of our experience we suggested that loose linings or melting hearths might be used to facilitate (1) the change from one class of alloy steel to another; (2) the examination and repair of the linings. This suggestion was subsequently adopted with some degree of success, but made the use of an auxiliary melting process absolutely essential. It follows that, with the steel acting as the secondary circuit, the only heat that one gets into the slag is by conduction. In consequence the slag is always colder than the steel, and seldom, if ever, really fluid. For this reason it is practically impossible to eliminate sulphur and phosphorus as in furnaces of the arc type. Owing to the large area of bath exposed, oxide of iron readily forms, and on entering the slag quickly forms a stout arch which completely envelopes the steel below. Once formed it is only with the greatest difficulty that it can be broken down and cleared. Our experience was that it was impossible to melt more than 10 per cent of turnings (swarf) or small light scrap with certain exceptions in this type of furnace, and that only with considerable difficulty. Owing to the field which is developed round any conductor of current, small pieces of light scrap become magnetized immediately they come near the bath. The result is that turnings and similar scrap cling not only to one another but to the shovel and iron frames of the bath covers, making the charging most tedious and difficult. All light scrap has to be continually pushed down into the liquid metal below, and again the iron rods usually used for this work become magnetized and adhere to the unmelted scrap in the bath. The difficulty of charging can be overcome by shutting off the current, but this involves delays and the greatest care must be observed to prevent the bath freezing at any point. This is a point for serious consideration in any scheme where quantities of light scrap are to be melted. Whilst turnings and light scrap generally are only melted with difficulty, unbent transformer-plate scrap makes a good charge, but only when carefully packed together and the packs charged by means of a pair of tongues. Owing to the small dimensions of the bath, it is equally impossible to melt any pieces of scrap weighing more than, say, 28 lb. This means that the material for the furnace has to be either specially selected or specially prepared. Add to this the difficulty of refining, and it immediately places the induction furnace, as a scrap melter, in a very unfavourable position when compared with the arc furnace. During the war, the electric furnace was the means of utilizing thousands of tons of turnings in a way that would have been impossible had the plants been equipped with furnaces of the induction type. Some of the difficulties mentioned above are minimized or eliminated in other furnaces of more recent design, and particularly in the Röchling-Rodenhauser type. British manufacturers availed themselves of the opportunity of examining the improvements of this type of furnace, and I think it significant that on turning to Mr. R. G. Mercer's paper, one finds no induction furnace included in the list of electric furnaces used during the war; in fact on page 264, Mr. Mercer states: "there are none in operation here so far as the author knows." It is also significant that America is credited with only three induction furnaces, compared with 274 furnaces of other types. When compared with the arc furnaces, the advantages are practically all on the side of the latter, the absence of electrodes and holders being really the only outstanding advantage that the induction furnace can claim and substantiate.

Mr. G. M. Brown: I suggest that the steel manufacturers and the electrical engineers are not showing a sufficient amount of confidence in each other; we are not getting down to details. Dr. Saniter has told us that better steel can be produced by the acid process than can be produced in the electric furnace. The question immediately arises as to how long it will be possible for the acid process to be carried on profitably in this country. During the war we have been driven to adopt the basic process more and more. We have had various figures quoted as to the consumption of power required to produce a ton of steel from an electric furnace, but no one has told us exactly the composition of the steel when finished; or in other words, what was

done to the material. With regard to the electric furnace, the general consensus of opinion seems to be that as far as ordinary steel is concerned it will be used at a refining instrument, but nothing has been said, for instance, about the American plant recently started in which a triplex process is being carried out and the electric furnace is the last link in the chain. These are matters which we might discuss with profit. With regard to the cost of power, it is quite evident that it was only possible, as a war measure, to pay 0·72d. per unit, as Sir Robert Hadfield did. At that price the production of ordinary steel by electric methods is not commercial, and will not be commercial when we return to ordinary conditions of life, and the sooner electrical engineers can get together and let iron and steel makers have power at ¼d. or less per unit, the sooner will they extend their business in electrical furnaces and accessories.

(*Communicated*) : Of the papers submitted those of Messrs. Mercer and Stobie contain the largest amount of useful information, and the others are valuable in that they contain the views of furnace makers and designers, although on some matters of importance these views are not in accordance with either theory or experiment. The first question arising from the consideration of the claims of the rival manufacturers is the proper basis for a comparison of their furnaces. It does not seem possible to make a really strict comparison of the merits of two furnaces unless they are run on charges of identical composition, and with a view to producing results also identical as nearly as possible. Such a test should extend over a lengthy period, for otherwise one of the most important features, i.e. reliability and the facility for making rapid repairs, could not be taken into consideration. Few firms are in a position to conduct a test of this kind, and none appears to have been made up to the present. Until such a test is made each maker will probably continue to claim that his furnace possesses advantages over others on account of the particular arrangement of the electrodes or methods of connecting them to the supply circuit, the arrangements, or lack of arrangements for bottom heating and so on. Mr. Mercer's paper gives the power and electrode consumptions per ton of steel made by a large number of furnaces of various sizes, but unfortunately the information he gives is not sufficiently complete to enable the reader to do more than generalize on the possibilities of the electric furnace as a means of working up cold scrap. He has included no particulars of the initial and final compositions of the various charges, although he has given the numbers of slags and the average times per heat. As far as power consumption is concerned, his figures indicate that it diminishes as the capacity of the furnace increases, rapidly up to 5 tons and then at a diminishing rate, but this is only natural in view of the diminution of radiating surface per ton of charge and the lower conduction losses to be expected from large furnaces. The number of electrodes in each furnace is not given, but the electrode consumptions indicate that abnormally large electrodes involve large consumptions of carbon or graphite per ton of steel made. Without efficient economizers or other means of protecting the electrodes this is only to be expected, for reasons very fully discussed by Mr. Stobie. As to whether, other things being equal, the size of the electrodes influences the consumption to any great extent, Mr. Stobie might be able to enlighten us : he should also be able to give, from his own experience, some interesting data on the effect of efficient economizers on the current and electrode consumptions per ton of steel made, and thus increase our indebtedness to him. The disposition of the electrodes is a matter that has given rise to much discussion in the past, and one on which the views of the various authors are divergent. None of the authors advocates the use of bottom electrodes similar to those of the Girod furnace, but they all recommend the use of one or more electrodes embedded in a conducting hearth, and that without reservation, excepting Mr. Stobie, and Mr. Sahlin's furnace seems to include every conceivable combination except that of Girod. Excepting the Stassano and Rennerfelt types of furnace, the chief objects to be attained are uniformity of temperature and the protection of the roof from unduly high temperatures and localized heating ; but some of the authors go further and claim that the arrangements of the electrodes in their furnaces are such as to cause effective circulation of the bath of molten metal, either in virtue of the fact that the hearth is made to act as an electrode or by electromagnetic action of the currents flowing through the bath. Mr. Stobie on the other hand denies that such circulation takes place and supports his contention by experimental evidence. There are two possible causes tending to produce circulation of the bath, viz. a steep thermal gradient which would cause convection currents in the molten metal, and the electromagnetic forces due to the currents. Messrs. Booth-Hall, Sahlin and Greaves all claim that convection currents are produced by the use of a conducting hearth with one or more electrodes embedded in it, and Mr. Greaves even goes so far as to compare his furnace with a kettle, although he admits that of the total energy supplied only 8 to 10 per cent can be applied to generate heat in the hearth. The analogy is quite mistaken, and for very good reasons, the most obvious of which is that in the kettle practically the whole of the heat is applied to the bottom where it is most effective in the production of convection currents. Further, water has a high coefficient of expansion and a low thermal conductivity, and its coefficient of viscosity is probably less than one-half or one-third that of molten steel, which is a good heat conductor. In view of these facts and the further fact admitted by Mr. Greaves, that the major portion of the heat used in an electric furnace is applied to the surface of the bath and in the bath in about equal proportions, it is difficult to see that the thermal conditions in a furnace are conducive to the production of the circulation claimed by the advocates of bottom heating. Indeed the conditions in the electric furnace seem more analogous to those in a test tube full of water when an attempt is made to boil it by applying heat to the surface of the water, and in small furnaces it is actually desirable to use bottom electrodes to obviate this state of affairs as far as possible. At least such a conclusion is supported by the remarks of Messrs.

Stobie and Bibby. The claim that a vigorous circulation is produced by the electromagnetic action of the currents flowing through the electrodes and bath is equally weak, in view of the fact that molten steel is non-magnetic and is also a dense and viscous liquid. Except in the immediate vicinities of the arcs the current densities are exceedingly low and the magnetic field strengths also, and nowhere is there any true rotating field such as is produced in an induction motor or any definite tendency to steady and uniform rotation such as would be required to overcome the inertia and frictional resistance of the liquid metal. These facts are demonstrated by the results of Mr. Stobie's experiments with a much less viscous liquid, viz. mercury. In short, neither the thermal nor the electrical conditions are such as to cause the circulation of the bath claimed by some makers as such a great advantage, and in that respect there is no difference between the electric and the open-hearth furnace. In the electric furnace there is, however, as pointed out by Mr. Stobie, some circulation of the slag caused by the blast from the electrodes. The most desirable feature of the electric furnace, and that which makers and designers would be well advised to develop to the greatest degree, is reliability. The electrodes should be easy to regulate, and automatic regulating devices should act with certainty and rapidity. The electrode holders should be of rigid and substantial construction and such as to obviate any possibility of jamming and breakage of the electrodes, and in this respect the gallows-arm type calls for great care and skill in design. The tilting arrangements should be of ample strength and of the simplest construction, and the whole design of the furnace should be such that renewals and repairs of the roof and lining may be executed with the minimum amount of delay and expense.

Mr. H. B. Toy: My reasons for installing an electric furnace at our works in Middlesbrough were, that during the war there was a very large quantity of steel turnings available in the district, part of which were being used in blast furnaces, causing considerable trouble to the pig-iron users. The Air Board at that time were urgently in need of nickel-chrome steels for the production of aeroplane crank-shafts, piston rods, etc., and it was apparent to me that these steel turnings could be very much more reasonably melted in an electric furnace for the purpose of making these special steels, and after 18 months' working I feel perfectly satisfied with the merits of an electric furnace for the manufacture of special alloy steels. I am doubtful whether an electric furnace will compete commercially with Siemens acid or basic steels of ordinary carbon quality, but this depends upon the price of current, electrodes and royalty. The designers of electric furnaces are not, in my opinion, justly entitled to the amounts generally charged for royalty. One designer offers a furnace with three vertical electrodes through the roof, another with two vertical electrodes through the roof and a conductor in the hearth of the furnace, another employs three electrodes entering the furnace horizontally, another prefers two vertical electrodes and one horizontal, and each designer either in the purchase price, or price per ton of steel produced, charges an unreasonable amount of royalty which, I consider more particularly in war time was not justifiable. I quite agree with Sir Robert Hadfield, and the figure he mentioned very nearly approaches our actual cost of working, but he did not mention that when these furnaces were first employed in this country the electrodes cost about £40 per ton, whereas our last consignment from America cost us nearly £140 per ton. I therefore cannot see how our present costs of working an electric furnace will be any guide to us as to what are going to be the costs when we come back to normal working, but I have every confidence that in the manufacture of special alloy steels the electric furnace has come to stay, and that mechanically the designs will be very much improved by the users.

Mr. W. J. Dawson: One point not mentioned by any speaker is whether a high voltage is desirable in electric furnace equipment. It seems to me that with a high voltage we get a high and quick input, and we are also able to reduce the diameter of the electrodes and in that way lengthen the life of the furnace roof. Another point is that with a quicker input of current and larger power we should be enabled to reduce the length of the heat and thus avoid radiation losses in the furnace, which of course all helps to economy in the production of steel. Then there is the question of electrode economizers. No doubt they are very desirable, but although there have been a good many devices they never seem to work, and it is really up to some of the electrode economizer designers to see if they cannot make them a practical proposition. Every steel maker recognizes the necessity of using such apparatus, but personally I have never found one yet that is really satisfactory. It works for a few days and then needs some repairs.

Mr. G. W. Partridge: I speak as a supplier of electricity. Many speakers have said that they could do a great deal if only electrical energy were cheaper. For example, Mr. Brown said that if he could get it at ½d. a unit that would be a satisfactory price. Sir Robert Hadfield says that if electrical energy were as low as 0·4d. electric furnaces would be a commercial proposition. One speaker has told us that he could get current in Norway at 30s. per electrical horse-power per annum. On a 50 per cent load factor—I assume that these electric furnaces are running on a very good load factor—that represents 0·082d. a unit. Electrical energy will never be obtainable in this country at anything like that price. Before the war, although we had to pay a high price in London for our coal, we offered current at less than ½d. a unit for electric furnaces on the south side of the River Thames. If members will only have patience until supply companies can purchase economical plant and generally set their undertakings in order, there will be no difficulty in supplying current at well below ½d., although I think ½d. a unit is, for the next two or three years, rather a low figure considering the high cost of plant and labour. The price of coal will probably fall, but I do not see much hope of a reduction in the price of labour. One speaker has suggested that there should be a special rate to encourage an improvement in the load factor. I quite agree to such an arrangement. I am sure that any supply company would be glad to give any inducement to

improve the load factor; specially low rates might be offered at off-peak hours. A large furnace demand, especially single phase, may have the effect of upsetting the regulation of the supply on a small distribution system. In my own case we began in a small way, but after having successfully supplied a large railway where we had a great number of short-circuits and overloads, a small thing like a furnace, even on the south side of the river in London, presents no difficulty to-day. For this reason I feel that any out-of-balance up to 20 per cent ought to be well taken care of on an ordinary large distributing system. I entirely agree with Mr. Mordey as to the difference in the efficiencies of furnaces, which is shown by the number of units per ton. If it makes so much difference to furnace users whether they pay $\frac{1}{2}$d. or $\frac{1}{4}$d. per unit for current, does it not make much more difference whether their furnaces take 600 units per ton or 5,250 units per ton, as shown in the schedule of figures in one of the papers? I think power-supply engineers should do all that they can to give a reliable supply to furnaces at a cheap price; but designers and users of electric furnaces should most carefully consider the question of improving the consumption of electric energy per ton, which appears to vary considerably and leaves much to be desired.

Mr. D. Sillars: Comparisons have been made between what is done in Norway and Canada and in this country in the manufacture of electric furnace products. I think that to some extent in a joint discussion of this kind it may perhaps be overlooked that the proposition is entirely different for pig-iron and for steel. The last speaker called attention to the difference in consumption between 600 units and 5,000 units per ton, and I would therefore point out that when we are making pig-iron from ore, or steel from scrap, there is always the question of whether we are going to reduce the material or not. In making a ton of pig-iron in a blast furnace, if it takes 20 cwt. of carbon, about 12 cwt. of that carbon will be required to reduce the oxide to its metallic state; but in steel-making this demand for energy does not exist, since the materials are charged in the metallic state. An electric furnace making pig iron, in addition to the melting of the material, has also to reduce the ore from which the iron is derived to the state of metallic iron. To accomplish this an amount of heat must be supplied equal to the heat of chemical formation of the reacting bodies, and this quantity in the case of iron oxides may amount to a third of the total heat required, while in the case of other alloys such as ferro-silicon the heat of formation of the oxide is about four times greater than in iron, and the energy required for smelting this alloy is proportionately increased. All this heat cannot, however, be supplied by electrical energy, since the oxygen liberated must be enabled to enter into some other combination, and carbon is the most convenient substance to supply for this purpose. To quote what can be done in Sweden or Canada avails nothing, because as long as we in this country have to produce electric power from coal, we shall never be able to do smelting. It will appear from the figures which I have mentioned why this is so. One speaker has said that a great deal of heat may be lost in the furnace through a hole in the wall. That of course should not occur, but it must be remembered that in making the steel the working furnace has a temperature which is almost the melting point of the refractory material, and if we attempt to do much lagging, the inside of the furnace would simply melt away and we should very soon have only the lagging left, and that would not last long. It is very necessary to allow heat to escape by radiation and convection unless we can find a higher refractory material than we know of at the present time. In connection with the construction of very large electric furnaces I do not see how such furnaces can be successful since we cannot apply heat over the whole of the bath. We apply the heat at certain points, and the larger the furnace the greater must be the number of openings in the roof. In a 60-ton open-hearth furnace the roof is already in a sufficiently critical position, and if it is pierced with, say, six electrodes, we shall get an extremely weak roof. Also, if we have bottom electrodes the bottom of the furnace will be weakened. It is very difficult to keep the bottom of a 60-ton open-hearth furnace in repair, but if, in addition, it were made conducting, the difficulties would be greatly increased and could only be overcome by the use of better refractory material than is at present obtainable.

Professor H. Louis: I think I am in a position to state definitely the cost of current in Norway. I was offered high-tension electrical energy at the factory terminals, alongside deep tidal water, at 27 kroner a kilowatt-year, that is 30s. a kilowatt-year, for a 24-hour load, i.e. this amount was to be paid irrespective of whether the current was used or not. The current was generated from water power and was available all the year round. That was the figure quoted to me for very large quantities before the war, and it is the most definite figure I can give. I think it makes it very clear why the suggestion of some speakers, that the one thing needed is to reduce the consumption of electricity in a steel furnace, does not solve the entire question. If in this country we cannot produce electric current at anything like the above figure, it does not help us in the least to cut down our electric consumption, because our rivals who use water-power can do exactly the same thing; the question resolves itself into the cost of electric power. There are, however, opportunities in this country for the production of power from waste gases. I need only mention the very successful work done by the Newcastle Alloys Company in generating electric power from the waste gases of coke ovens, and thus working large electric furnaces.

Mr. A. P. Pyne: I cannot lay claim to any practical knowledge of this subject but have made a number of inquiries regarding electric furnaces and have visited a good many. I have been principally struck with the enormous difference in running costs. Take, for example, a furnace which I recently saw in Scotland. Those responsible for its operation were entirely satisfied and would be very sorry to go back to their old process; they propose to repeat the furnace. They gave me their running costs which were very satisfactory.

Shortly afterwards I visited another furnace further south. This was of exactly the same size as the one in Scotland and turned out the same class of steel. I was again given the running costs which were, however, 2½ times those of the Scotch furnace. The engineer who showed me the figures said: "Do not on any account put down an electric furnace." If these costs were any criterion of what was going on in the furnace I could quite share his view. I had hoped to hear during this discussion an explanation of these wide differences. In the course of one's inquiries, one comes to the fairly obvious conclusion that there is very little to choose between, say, three or four of the more usual types of furnaces either electrically or metallurgically; nor with furnaces intelligently operated is there much difference in the consumption of electrodes and of electrical units per ton. There are, however, slight mechanical differences which will exercise from time to time an important bearing on the running costs, but by no means sufficient to account for the discrepancy indicated above. It is reasonable to suggest, therefore, that before condemning an electric furnace steps should be taken to ensure that the handling of the furnace is not at fault. I should like to say that I am a great believer in automatic control in any but very small furnaces. As a result of a good many years' experience of automatic control, I can say that it is usually far more reliable than the human element. If it is found unsatisfactory in any specific case, it is probably due to unsuitable design. If, however, automatic control is complicated, an endeavour should be made to simplify it; if it is found liable to break down, alter the design and so make it more reliable, but do not condemn automatic control offhand. With regard to transformers, there are designs on the market which cannot be repaired on site; these should be avoided. If they have to be sent to the maker's works much valuable time is lost. It is all very well to say have spare transformers, but they are expensive and it is not everyone who cares to incur such expenditure, particularly as transformers sometimes last for years without breakdown, in which case a spare transformer is capital lying idle.

Mr. T. M. Service: As several steel makers have expressed adverse opinions on the quality of steel made in the electric furnace, I should like to give my experience at the works with which I am connected. We have a small 35 cwt. electric furnace. This furnace has been employed on all qualities of steel, but principally nickel chrome. We have found that in this type of furnace there is greater control over the temperature and also over the composition of the steel, with the result that the product is superior to any produced from the ordinary open-hearth furnace. Many of the ingots made have been split and the surface polished and etched, and prints taken from the polished surfaces. These prints show that the steel is much more solid than that made in other types of furnaces. We have specially investigated this class of steel for non-metallic impurities, and we find that owing to it being possible to regulate the temperature very efficiently, this type of defect is practically eliminated. It may be pointed out that these good results might be due to the small furnace, but in order to test this we arranged with the Stobie Steel Company of Newcastle to make two 10-ton charges in their furnace. The steel was to be made of armour plate scrap, and the resulting ingots were to be made into hollow forgings of a very high class. The two charges were made very satisfactorily, and the ingots when cold were trepanned, hollow forged, and treated in the usual way. These forgings passed test on first presentation, and the tests did not show any signs of non-metallic impurities. In order, however, to make certain that these did not exist, we asked the department who were machining the forgings to watch them very carefully outside and inside and report if any sign of non-metallic impurities was discovered; no trace at any stage was noticed, and as a further precaution a very light cut was taken off the outside. The cutting remained intact without breaking, showing that there were no defects. As the result of this satisfactory experience we were asked if we could not produce all the articles for this class of work from the electric furnace. It should be added that bad steel can be produced from an electric furnace equally as well as from any other type of furnace, but this can be avoided by having trained men in charge of the operation.

Mr. A. M. Taylor: I should like to make a suggestion. It seems to me practicable to supply a single-phase furnace from a three-phase main, by superimposing the single-phase load at the generating station, in such manner that there shall be no material disturbance to the existing consumers on the mains, and at any periodicity which might be useful to the furnace people. The demand for single-phase furnaces might be met in that way by the large corporations and others whose mains go close to the makers' works, and it would cost the corporation very little indeed to give the supply. Another point is the cost of power. I had occasion to go very carefully into the actual "running" costs some time ago in connection with a supply to large batteries, and the figures which I obtained will, I think, not be far wrong, except that they were at pre-war prices. I made out that the actual "running" cost of power, apart from all charges of the nature of fixed charges, was only of the order of about ⅛d. per unit. If we can get an off peak load—for example, if the steel makers could take their supply during the night time—I do not see why something like ⅜d. a unit might not be charged under that limitation. The rest is merely a question of load factor. If the steel makers will only give us the load continuously all the hours of the year, I do not see why something between ⅜d. and ⅝d. might not be possible in many cases. At any rate a sort of mixed rate might be offered, whereby they had a low rate at night and a different rate during the day. Electrical engineers should remember how they captured the motor load some 15 years ago, and how fortune favoured their attempt to offer current at prices which seemed almost ridiculously low to the average station engineer, and they should repeat those tactics now.

Mr. A. Imbery (*communicated*): The papers are chiefly confined to arc furnaces, and this I think is rather unfortunate, as there are other types of furnaces which have great commercial possibilities for steel and

allied trades. I should like to make reference to a furnace which has been put on the market in the United States and possesses several special and unique features. This furnace is a high-frequency induction furnace and can be operated at high voltages, thus obviating the capital outlay necessary for transformers, which are necessary on the arc and induction types. Another important advantage is that no electrodes are necessary for the operation of this furnace, thus cutting out a certain amount of heat losses and improving the mechanical and electrical construction, in addition to obviating certain difficulties which are inherent to all types of arc furnaces. Particulars of this interesting furnace were given before the Faraday Society some little time ago, and details are published in their *Journal*. Unfortunately these furnaces are only made at present in small sizes up to about 50 kw. The chief advantage, to my mind, of this type of furnace is that we can smelt both ferrous and non-ferrous metals without electrode losses, and no contamination of the charge is obtained during the smelting or refining period. The figures given by Mr. Mercer respecting the performance of the various furnaces in this country are very interesting and prove a very valuable summary of the operating cost of electric furnaces. According to these figures we do not appear in this country to be getting anything like the efficiency and the number of heats per day that are claimed for the American electric arc furnaces. According to the American claims, the working cost of their arc furnaces is much less than the figures obtained in this country. Some tests taken last August on one of the American 3-ton arc furnaces showed that these melted on the average 49,000 lb. of metal per day, giving an average of slightly better than 8 heats per day. They claim that the current consumption with this type of furnace averages 580 units per ton, and it has been possible to make 11 heats in 24 hours on this furnace. The transformers for operating these furnaces are of the polyphase water-cooled type, and are supplied in the following capacities for various sized furnaces: 3 tons, 1,000 k.v.a.; 6 tons, 1,800 k.v.a.; 10 tons, 3,000 k.v.a. The transformer ratings are based on a 40 degrees C. rise in temperature at full load. The furnace operates with a live bottom so that each electrode comes into operation when touching the charge. At the melting down of the charge the furnace is arranged to operate with a relatively long arc and high voltage. In refining, the length of the arc and also the voltage are reduced, without very materially altering the current. It is claimed that the long arc is an advantage in melting down a charge of cold scrap owing to the arc gyrating over a longer radius around the electrodes and thus fusing or melting more of the metal. A shorter arc is an advantage when refining, as the greater arc length has a damaging effect on the refractories. I certainly think it is a step in the right direction to operate the furnace at as high a power capacity as possible, so that we can get the tonnage output at the minimum cost. The capital expenditure required for electric arc furnaces, complete with transformers and switchgear, is very high compared with other methods of steel production, and I certainly think it is up to electrical engineers to bring down the capital charges very considerably, especially for the smaller types of furnaces. I do not hold any brief for the American electric furnace, but I think we could take a leaf out of their book with some advantage. In conclusion, I think there will be considerable development in the electric furnace work in this country in the brass and allied trades. I consider that the resistance type of furnace offers considerable commercial advantages compared with the existing methods of crucible smelting, and I think it is rather a pity that no reference has been made to the resistance types of furnace for low-temperature work and the smelting of non-ferrous metals.

Mr. E. C. Sprague (*communicated*): Mr. Bibby, in his paper, and speakers in the discussion, have raised the question as to when electrode manufacturers would produce electrodes of a larger diameter than those now available. Speaking for graphite electrodes, I can say that the manufacturers at Niagara Falls realized some time ago that this demand for larger electrodes would be made, and at that time they equipped their plant with the necessary machinery and apparatus for producing large graphite electrodes, probably up to 16 inches diameter. Unfortunately the manufacture of graphite electrodes is not the simple process indicated by one speaker, and although the tools for manufacturing larger electrodes are on hand it remains to learn how to use them properly. No one who has not had actual experience in this particular work can realize what a big manufacturing problem it is to increase the size of graphite electrodes from 12 inches to, even, 14 inches, how many months of non-productive experimental work are involved, how many costly failures must be experienced. The difficulties are far greater than indicated by the proportional increase in the diameter. During the war the tremendous demand for all classes of electrodes made it impossible for the Niagara Falls manufacturers to spare time, equipment or power for experimental work which, for a considerable period, was bound to be non-productive. Now, however, it will be possible to take in hand the production of these larger sizes till success has been attained. I should like those interested in this question to know that the manufacturers of graphite electrodes have the problem actively in hand. In connection with this same question, it seems to me that perhaps the users of graphite electrodes in this country are a little conservative about forcing these electrodes to carry the maximum current. Mr. Mercer and Mr. Stobie intimated that 10,000 to 11,000 amperes was about the limit that could safely be carried by a 12-inch graphite electrode. There are, however, installations on the Continent and in America where 12-inch electrodes are being used regularly to carry 15,000 to 20,000 amperes and with apparently satisfactory results. I realize that many other things than the actual carrying capacity of an electrode determine the maximum current that can be used on any particular size, but I think the possibility of increasing the amperage generally used on these larger electrodes should receive careful consideration. If, as stated by Mr. Stobie, fully 75 per cent of the electrode consumption in an ordinary electric furnace is due to surface burning, naturally the smaller this surface the less will be the

proportionate loss from this source. In regard to the statement by one speaker that before the war his electrodes (presumably graphite electrodes) bought in America cost him £40 per ton, while the last lot received had cost him £140 per ton, I can only say that by far the larger part of this increase must be blamed to the increase in the cost of ocean freight, because the manufacturers of graphite electrodes have not increased their prices to anything like this extent.

Mr. W. Travis (*communicated*): One important point introduced by this discussion is the scope of electric furnaces, and several speakers have referred to the electric furnace as being of no use for turning out large quantities of steel. This is quite contrary to the views of many steel makers who have given attention to this problem, and it may be of interest to mention that a large plant is being put down in this country for refining hot metal in the electric furnace. The present practice is to take molten pig from the blast furnaces into the basic open-hearth furnaces, and in the new plant it is proposed to charge the molten pig into a basic Bessemer converter and after a short treatment transfer it to a Greaves-Etchells electric furnace where it will be completely refined. The gases from the blast furnaces are used for generating electrical power, and energy can be generated at very much lower prices than it is possible to obtain it from power companies' mains. It is hoped by this Bessemer-electric process to produce steel at a lower cost than is possible by the present open-hearth method. That steel makers should be prepared to spend vast sums of money in the United States and in this country on developing schemes of this description proves that there is considerable confidence in the production of electric steel in large quantities at a reasonably low price. In connection with the scope of electric furnaces, no one appears to have referred to their use in connection with the manufacture of steel castings, for which they are particularly suited and are rapidly replacing other methods. It would appear that the Booth-Hall Furnace (Fig. 3, page 248) and the Stobie Furnace (Fig. 1, page 208) are identical with the Electro-Metals furnace, the mere introduction of two hearth connections making no practical difference in the operation of the furnace. The statement on page 248, that two sets of grids in the hearth are electrically insulated from each other, requires further explanation, as they are embedded in a conductive hearth. The introduction of an auxiliary electrode in the Booth-Hall furnace is one that does not commend itself from an operation point of view, as it only increases the electrode consumption with no compensating advantage. The energy consumption given by Mr. Booth on page 249 compares very favourably with English practice as given in Mr. Mercer's paper, but the figures as to energy consumption are very misleading. In the United States steel foundry practice is usually considerably ahead of our practice on this side, and good quality scrap is available in considerable quantities. Acid lined furnaces are therefore almost universal for the manufacture of castings, and electric furnaces are used merely as melting machines, the metal being teemed immediately it reaches casting temperature. This is quite contrary to the usual English practice, where basic furnaces are almost always used and the steel refined under two slags. The furnaces shown in Figs. 2 and 3 in Mr. Stobie's paper have the very great disadvantage that the electrodes are not independent of each other and special means of electrode regulation have to be adopted. Electrically they appear to have no advantage over the original Héroult system. Mr. Stobie makes many definite statements with which one can disagree; for instance, on page 268 he states that "Long experience has shown that bottom electrodes'. . . are very undesirable in large furnaces." I am quite convinced that there is not the slightest foundation for any such assertion, as bottom electrodes have been used with great advantage in all sizes of furnaces. Provided the current density per square foot of effective hearth area does not exceed 500 amperes, no difficulty whatever will be experienced. There are, no doubt, great advantages in using an efficient economizer, and there are several efficient types now in use giving much better results than those given by Mr. Mercer on the Stobie furnaces. The "telescopic" type shown in Fig. 8 was tried long ago in several Sheffield works and discarded as useless. It is now generally accepted that circulation of the metal in the bath is not caused by the magnetic forces produced by current passing through the metal, and as automatic circulation of the metal is admitted to be a very desirable function of any electric furnace, the "Greaves-Etchells" system appears to have a great advantage. In any furnace with top arcs only the top layer of the bath is superheated, while the bottom may be comparatively cold, and frequent rabbling of the steel is necessary to ensure a uniform product. In the Greaves-Etchells furnace, if a bar is placed in the metal and the voltage measured at full load between the bar and the steelwork of the furnace body, a reading is obtained of 6 to 10 volts, and if the heat generated by the hearth is also measured it is found that 8 to 10 per cent of the total energy applied to the furnace is generated in the hearth. This feature is most effective in promoting circulation of the metal. This circulation also accounts for the rapid deoxidization of the metal in the furnace, as the whole bath is brought into constant contact with the slag. A simple test of the efficiency of bottom heating is in making, say, an alloy steel, where an element such as tungsten is used. The melting point of the steel before tungsten is added is approximately 1,475° C., and the specific gravity say 7·8. To this may be added say 10 per cent of tungsten, which has a melting point of 3,267° C., and specific gravity 19·02, and the only thing that can happen in a top-heated furnace is for this to go straight to the bottom and stay there. In a furnace with the Greaves-Etchells system, fresh and saturated steel is constantly moving in contact with the tungsten until a balance is automatically reached. An additional advantage of generating part of the heat by resistance of the hearth is the corresponding saving in the electrode consumption. Mr. Bibby's statement that the energy generated in the hearth is almost entirely lost may be true of furnaces of the Electro-Metals type, but does not apply to a furnace with a properly designed hearth, as the outside casing at the bottom is usually much cooler than the sides of the furnace.

[The authors' replies to this discussion will be found on page 298.]

NORTH MIDLAND CENTRE, AT SHEFFIELD, 29 APRIL, 1919.

Mr. S. E. Fedden : It may be of interest if I give a short résumé of the advance of the electric furnace industry in Sheffield. In 1882 the late Sir William Siemens melted 20 tons of steel electrically and thought he had done a very great thing. In 1902, pig and scrap iron were made into steel on a commercial basis in electrical furnaces, but practical men took some time before they would even try the experiment. The first firm to do so in Sheffield on any large scale was Messrs. Edgar Allen & Company, who installed a single-phase furnace, and shortly afterwards Messrs. Thomas Firth and Sons followed suit. These furnaces were run off motor-generators and we had very little trouble. The next furnace installed was in 1910, when we tried to supply a two-phase furnace from transformers direct. That was an Electro-Metals furnace and we had a lot of trouble with it. In 1914 we connected up 11 furnaces of different types taking 13,000 kw., and 18 furnaces taking 14,000 kw. were added in 1917. In 1918 we added a further 7 furnaces, so that altogether we connected up in a very short period furnaces taking an output of no less than 35,400 kw. That, in addition to the increase in the motor and lighting load, made us wonder how we were going to supply them. We practically doubled the size of Neepsend power station, laid hundreds of miles of mains, and were able to cope with the very rapidly increasing demand, so much so, that the units sold increased from 26 millions to 172 millions in three years, and our maximum load from 14,000 kw. to 59,000 kw. Turning now to the papers, the Booth-Hall and the Sahlin furnaces appear to be merely modifications of the Electro-Metals furnace. In Mr. Mercer's paper, on the first page he says the nominal output in tons per month is based on five-sevenths of a week, which represents a nominal load factor of about 70 per cent. In the second column on page 255, Mr. Mercer shows that manufacturers only use their furnaces for castings 46 per cent, and for ingots 59 per cent, of the nominal load factor. That reduces the load factor to about 30 per cent, and if we assume the diversity factor for the whole system to be two, that brings down the individual load factor on each furnace to 15 per cent. For such a load manufacturers ought to pay 3d. or 3½d. a unit ; whereas the Corporation of Sheffield have been supplying electrical energy at 0·6d. per unit for the manufacture of steel. In Table 5 on page 256, the figures for " units per ton " are 900, 1,830, 5,250, 1,950, and 1,000. Surely that shows a great lack of care and knowledge on the part of those who are running these furnaces. On page 262 Mr. Mercer refers to the failure of supply. Of course we connected up many more furnaces than we could safely supply from our plant, but we had to do so because of the war. We had an arrangement by which we could telephone direct to manufacturers and ask them, when necessary, to reduce the amount of power taken by the electric furnaces.

Mr. G. E. Dells : The figures given by Mr. Mercer show, first, the possible output of steel from the furnaces installed, and secondly, the actual output. If a third figure could have been given showing the finished weight of steel castings produced by the same furnaces, its smallness would have occasioned considerable surprise. As a matter of fact the electric furnace output of steel castings until quite late on in the war was comparatively small, the bulk of the output coming from the Siemens furnaces and the side-blown converter.

Mr. W. J. Howard : The Booth-Hall furnace, as Mr. Fedden said, is an Electro-Metals furnace with the addition of a few talking points. Instead of having a common bottom two grids electrically insulated from each other have been introduced, but if the bottom will carry current I do not see how the two grids can be insulated. In regard to the diagram of connections with the three-phase type, I do not know what influence the third electrode would have, but I do not think the arcs would be steady. If used as shown in the paper, they would blow each other out. Mr. Mercer might have mentioned the most suitable melting voltage, which is also omitted from all the papers. If we are to get cheaper electrical steel I think it will be by an alteration in voltage. In many of the older furnaces the voltage is far too low, and could be increased by perhaps 25 per cent. Only in this way shall we get a greater amount of energy into the furnaces in a short time and thus save radiation losses. The radiation loss on a large furnace might represent 450 kw. By saving an hour in melting with a large furnace we might save 450 units. If the voltage is increased we shall also effect a saving on electrodes and also on the refractories of the furnace, because the molten metal will be in the furnace for a shorter period. Considering Mr. Stobie's paper, on large-size furnaces he appears to have reverted to single-phase working. I think it is a mistake and hardly fair to the supply authority to try to make these large single-phase furnaces work direct off a three-phase supply. Mr. Stobie mentions six or seven points in connection with furnace transformers. I assume that he is referring to transformers which are used with his particular type of furnace. Four of the points would not apply to two-thirds of the electric transformers that are working in England to-day, and I am not quite sure whether such transformers are the best type for furnace work. I should like to ask the author why he states that as much as possible of the total reactance should be incorporated in the transformers. The size of transformers is thereby increased, and also their cost. Moreover, the reactance could not be reduced if desired. I consider it would be far better to build a transformer with as little reactance as possible and to add reactance in the form of iron on the low-tension leads. This could be done at one-fifth the cost. The heat would be outside the transformer and would not do any damage. To divide the transformers in the middle of the primaries in order to keep them balanced for voltage alteration, would double the number of tappings and increase the quantity of switchgear, resulting in very expensive and complicated switchgear and high-tension cable arrangements and rendering it impossible, in my opinion, to make a good job. My idea of furnaces on an extra-

high-tension supply is that they should have as little switchgear as possible, but the best they can get, and any devices for changing the pressure should be operated under oil. I am not sure whether it could be done with the type of transformer having tappings in the centre. I wish that designers of new furnaces would try to improve on the present three-phase furnaces. I am of opinion that such furnaces are more reliable from a transformer point of view. Scott-connected transformers are possibly suitable for lighting and power loads, but if a two-phase furnace control switch is closed whilst one electrode is making contact with the metal, five times out of six the transformer will break down due to surges. I think reliability should be one of the first features of an electric furnace, and I am quite sure that three-phase furnaces are the most reliable.

Mr. E. H. Crapper: I was very interested in Mr. Howard's reference to the desirability of raising the pressure, which, I assume, implies a reduction of current. I believe that a furnace known as the Belk furnace has been recently introduced in which the pressure is about 100 per cent greater than the usual. On the other hand, it seems to me that to raise the pressure will mean a longer arc, with the possibility of more serious heating of the furnace cover. If, however, the economizer is so great an improvement, higher voltage and smaller current may mean greater economy and better regulation. With reference to Mr. Stobie's remarks regarding the reactance of transformers, engineers accustomed to the design of transformers should settle such matters. I understand that the information about wave-form was obtained from an oscillogram. Was this obtained across the terminals of the furnace and how does it compare with the wave-form of the supply? If we get the effect mentioned, it implies the existence of harmonics, and it may be that the current wave remains sinusoidal because one harmonic may smooth out others and the fundamental only remain. There is also another statement that I cannot understand, viz. "The current wave approximately retains its sine shape and a lagging power factor results without any phase displacement." On the next page the author states that "the total impedance at the moment of starting a large furnace with poor scrap sometimes reaches over 90 per cent." Of what is it 90 per cent?

Mr. W. E. Burnand: I was never able to understand why the passage of an electric current through molten metal should cause the metal to circulate; but since it was put forward as an observed fact by so many people, there seemed little room for argument. Mr. Stobie's experiments, which appear to be conclusive, are therefore welcome as reconciling practice with theory. At the same time I will not say that it is impossible to cause circulation by getting a relative displacement of current flow to magnetic field similar to that utilized in the homopolar generator. The arrangement mentioned by Mr. Stobie, of apparently a direct current in the external magnet, would give an alternating stress and a slight vibration only. This would be, of course, very feeble, as very little of the external flux would penetrate through the steel shell of the furnace. Another fairly obvious electromagnetic method of inducing a circulation of the molten metal would be by means of a rotary magnetic field which could be obtained by two or more low-voltage heavy-current circuits outside the furnace lining but inside the steel shell. This would be, of course, a bigger job than the cotton-covered winding in an electric motor, but it could be done if it were worth while. Again, most two-phase and three-phase furnaces are apparently intended to be two or three single-phase furnaces inside one shell. There seems to be rather a fallacy in connection with this. The idea seems to be that if we keep the transformer windings entirely separate, one phase from the other, there will be no intermingling of the current in the bath or in the transformer windings.

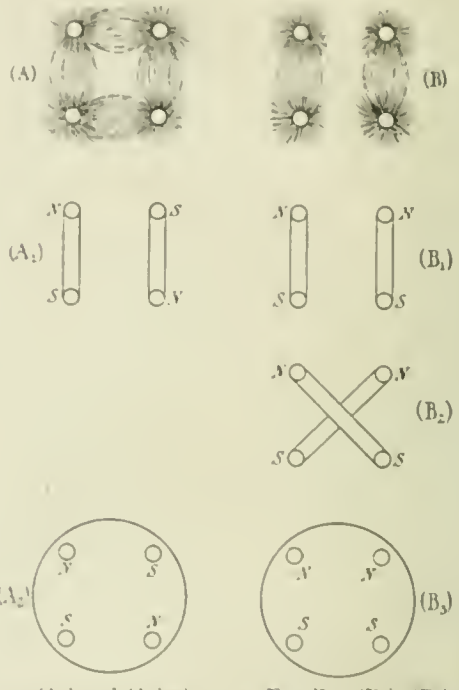


FIG. A.—(A_1) and (A_2) give the distribution of lines shown in (A).

FIG. B.—(B_1), (B_2) and (B_3) give the distribution of lines shown in (B).

NOTE.—(A_2) and (B_3) show straight magnets on a common yoke, which in this case is a disk, but could be a ring or a cross without observable difference in its effect.

As a matter of fact it does not make any difference whether the transformer windings are separate, star-connected, or mesh-connected; the distribution of current in the furnace is exactly the same and will vary in the bath strictly in proportion to the potential difference between the electrodes. An analogy is the U-shaped magnet. If we take two magnets to represent two phases we can arrange them as we do the electrodes in the metal bath, and a few iron filings sprinkled on a piece of paper (smooth) or card over the magnets will indicate the direction and strength of the flux from and between the poles. It will be found that instead of the currents crossing conveniently from one electrode to the other as in Fig. 2 of Mr. Booth's paper, it is possible for the fluxes to arrange themselves in two, more or less parallel, circuits or for them to arrange themselves in series, and that the external flux is just the same with the two separate U magnets as with

the corresponding magnets of the same polarity utilizing a common yoke. I have drawn a diagram (Figs. A and B herewith) showing this, which, though elementary, I was unable to find in one or two textbooks, and it may therefore be useful for reference. It is interesting to notice that when the two U magnets are crossed as in (B_2), Fig. B, we get no crossing of the flux from the poles but only two paths of flow as in (B). The magnets virtually act in series, so that to cross the circuits is actually a disadvantage rather than otherwise, though I doubt if there would be any perceptible difference in practical operation except due to secondary causes unconnected with the crossing of the circuits. With two phases we do not get quite the same effect as that shown by the two magnets. When the currents are the same strength, or in phase, we get the same effect, but when the current in one phase is zero and in the other is a maximum, we get the actual crossing shown, viz. diagonally from one electrode to the other of opposite potential, the electrode at zero potential of course having no effect. During the remainder of the time we get a certain amount of intermingling of the currents whether the transformer windings are entirely separate or not. As the passage of current through the molten bath has no appreciable heating effect owing to the low resistance, and as the supposed tendency of the metal to circulate does not exist, and the transformer circuits have no effect on the distribution of current in the furnace except as this may affect the potential at the electrodes, many claims made for different arrangements have only a poor foundation, but there are still real differences between furnaces in connection with the design and perfection of practical details. The load on transformers is very severe and much above what is often specified, and when a furnace-maker calls for 100-kw. transformers I think it is well to quote for 200-kw. transformers with a 100-kw. label and a 250-kw. price to make up for the cost of the extra bracing required. The result is far cheaper than to install smaller transformers and overload them. With regard to the voltage-wave distortion mentioned by Mr. Stobie on page 272, the dip in the top of the voltage wave is due to the reactance or impedance external to the furnace, in conjunction with the characteristics of the arc, and we get a power factor less than unity without a lagging current. It would be more correct therefore to call it a lower power factor without phase displacement, or at any rate not due to phase displacement. This of course applies to the power factor across the arc, as the current as a whole is always lagging behind the voltage wave at the transformer terminals. Referring to the last paragraph in Mr. Stobie's paper regarding the arc-blowing action, I think what happened was a variation of the "pinch effect." It is well known that if a large current is passing through a conductor there is a compressive or pinching action, and if the current density is sufficient that action will pinch the molten metal into two and separate it. The arc ensuing vaporizes a certain amount of metal and blows the molten metal away. That breaks the arc. When the arc is broken the vaporizing effect ceases. The molten metal then rushes back and causes a short-circuit as mentioned in the paper.

Mr. J. L. Thompson: The failures in service of transformers on the earlier furnaces installed in this country were not in the main due to any fault of the transformer manufacturers. Failure occurred due to the following reasons, which are based on my personal investigations: (1) Furnace makers not knowing the exact requirements as regards reactance characteristics, voltage range, load requirements and unbalanced loads. (2) The bad lay-out of the heavy low-tension leads. (3) The bad ventilation of the transformer substations. (4) The unskilled labour used for operators, and the negligence of these operators in keeping the apparatus clean and in good condition. With reference to (1), I designed apparatus a few years ago to a furnace maker's requirements, a specification in which a reactance of only 1·5 per cent was required, while now that same furnace maker requires 10 to 12 per cent reactance, and sometimes even higher values. Another furnace maker about the same time required 17 per cent reactance, while now 8 to 10 per cent is his requirement. With reference to (2), I have been called in on several occasions to explain why transformers would not give the requisite power, and on each occasion I have found that it was due to the crude and unscientific lay-out of the low-tension circuit which resulted in the whole of the voltage being absorbed in the circuit so that none remained to strike or maintain an arc in the furnace. A reconstruction of the lay-out, which in each case had been originally made by the furnace builder or consulting engineer, remedied the defect. I have detailed these points to draw attention to the fact that if the furnace makers had initially taken the transformer manufacturers into their confidence, much trouble and expense would have been saved and the development of the electric furnace would have been more rapid. Mr. Stobie under heading (4) gives a series of seven requirements for furnace transformers. With some of these requirements I agree, but others give cause for comment. Under (1) he states that the current density should be low, and later he says it should not exceed 1,260 amperes per square inch. I should like to know how he arrived at this figure. When dealing with heavy currents, current density alone is not the limiting factor of heating. I know from experience that the above is too low a value and results in increased eddy-current losses due to heavy sections of copper and reduced cooling, since with increased copper section ventilating ducts cannot be liberal. This will be appreciated when one considers that the eddy-current loss in the low-tension copper often equals the I^2R loss, and with high-reactance transformers often exceeds it. For 500 k.v.a. a current density of 1,750 amperes, and for 4,000 k.v.a. with forced cooling approximately 3,000 amperes per square inch can be safely used, if the British standard rating is adopted and adequate ventilating ducts are provided. Under (2), ventilating ducts must be carefully considered. I agree with this, and would go further and say that the ducts should be many, and one for every $\frac{3}{4}$ inch of coil depth as a minimum, to prevent internal heating. I agree with item (3), except that bracing should be provided on all sides of coils in which movement is possible, and should be so designed as not to interfere with adequate ventilation. Item (4) suggests that all

low-tension coils should be taped; with this I disagree, from the point of view of cooling and insulation. A solid insulation barrier between turns is necessary and a bare surface in order to allow the heat generated to flow without impediment into the cooling medium. If a poor quality of transformer oil is used, to tape the coil or to tin the copper would reduce the possibility of sludging. I agree in part with item (5), but provision must be made for possible expansion of the copper under high working temperatures, since the clamps are usually fixed when the windings are cold and serious distortion may take place if no allowances are made in any one direction. I also agree with item (6), but I should like to remark here that the magnitude of the mechanical stresses possible on the transformer windings is nothing like the magnitude of the stresses on a power transformer. The magnitude of these stresses on power transformers was fully dealt with in a recent paper on "Large Power Transformers."* To give an idea of the stresses, let us take first a power transformer: 2,200 k.v.a. single-phase transformer with 5·5 per cent reactance, 25 periods. Here the stress on the end coils (sandwich type) in an axial outward direction on a dead short-circuit is approximately 75 tons. Taking the same size of transformer for furnace work with 10 per cent reactance, short-circuited by dropping the electrodes on to the metal during the melting period, with a power factor of approximately 0·8, i.e. with 60 per cent reactance in transformer, leads, and furnace, the stress on the coils in an outward direction is of the order of 0·5 ton. If the electrode short-circuits the transformer through a molten bath, the power factor being approximately 0·2, the reactance of the circuit is approximately 38 per cent and the stress on the coils in an outward direction is of the order of 1·2 tons. If the transformer were accidentally short-circuited across the low-tension terminals, then with a reactance in the transformer of 10 per cent the stress would be approximately 24 tons. From the above it will be seen that the magnitude of the stress is not excessive during operation, but where the severity comes in is that this stress, though low compared with power transformers, may take place very frequently and as often as three or four times a minute during the melting period and several times during the molten stages of the process. This necessitates good clamps well locked and leads (the low tension especially) well cleated to prevent movement. Clamps in a radial direction are not necessary especially if the transformer is correctly designed with the proper turn centres of the low-tension and high-tension coils in line. If this is not possible then the stress on the high-tension coils can be directed upwards on to a suitable support, and the low-tension cleated and held rigidly in clamps, thus leaving the top and bottom of the coils in view for inspection and for ventilation. Item (7) is a very contentious point, and I am in agreement for transformers of moderate size up to 500 k.v.a. if the reactance does not exceed 10 per cent. For larger sizes where the low-tension current becomes heavy, the accommodation of this current necessitates many groups of low-tension coils in parallel, and hence a low reactance, unless magnetic shunts are used, which is undesirable. In this event the reactance, for design reasons and to reduce losses, should be external and in the high-tension mains. I do not think Mr. Stobie will get satisfactory operation from the connections shown in Fig. 3, and I should like to know if he has in operation a furnace with such connections. I would suggest that a delta high-tension arrangement would give a better and more stable condition in service. In conclusion I should like to state that, from my experience, the furnace transformer of the future will have to be on the following lines for large installations: A true transformer of one ratio and no tappings, having a low internal reactance, with an external reactance on the high-tension side to steady the arc and protect the apparatus from current-rushes and voltage-surges. The voltage variation would be obtained by a booster in the low-tension circuit, or by means of a regulating transformer or induction regulator. This has the advantage that all operating gear may be situated apart from the main transformer and suitably housed. Also, in the event of failure of the regulating gear, the main transformer could still be used on the common voltage during repairs.

Mr. D. G. Jones (*communicated*): It is interesting to notice from the summarized results in Mr. Mercer's paper how widely different are the conditions under which some of the furnaces are run. The units per ton of steel vary between 600 and 6,000. Attention might be drawn to the thermal efficiencies of some steel-producing furnaces. Taking a fairly good result, viz. 650 kw.-hours per ton of poured steel, and assuming melted steel to contain 630 therms per lb., we have a net efficiency of 63 per cent from the supply mains. This result is not at all bad, but is not the best that can be obtained. Taking the overall efficiency from the coal bunkers of the power station, and assuming the coal to have a thermal value 13,500 therms when burned at the rate of 1·77 lb. per kw.-hour, the overall efficiency comes out at 0·46 per cent. This indicates how important it is that our power stations should be brought up to a much better thermal efficiency. Take another case, a crucible melting hole—a type of furnace much in vogue in Sheffield. This furnace requires 3 tons of coke per ton of steel. If we take the coke at 12,000 therms per lb., and melted steel as containing 630 therms per lb. as before, the efficiency equals 1·044 per cent. Similarly, with a Siemens open-hearth furnace using 8 cwt. of coal at the gas producers, which is a fairly good result, the thermal efficiency is 12 per cent. It is very evident, therefore, that power station engineers are not the only people who waste coal, and that there is a very great need for further research into coal saving methods all round.

The authors' replies to this discussion will be found on page 208.

* Journal I.E.E., vol. xl., p. 510.

South Midland Centre, at Birmingham, 7 May, 1919.

Mr. F. J. Moffett: Unfortunately none of the authors is able to be present this evening to introduce the subject: I have therefore undertaken to do so.

The electric steel furnace is essentially a crucible with the heat applied internally instead of externally. The principal advantages, as compared with a combustion furnace, are the high temperature, high efficiency, and exclusion of air.

High temperature.—The combustion furnace is the most economical method of heating metal up to, say, 1,000° C. The limit of temperature obtainable in a furnace heated by the combustion of fuel is about 1,500° C. This is due to the heat at high temperatures being carried off by the hot waste gases and to the fact that gases dissociate at this temperature. The temperature of the arc is roughly 3,500° C. Temperatures of 2,000° C. and upwards are readily obtained in the electric furnace—in fact the limit of temperature is in practice set by the temperature which the lining and roof of the furnace will withstand. It is difficult to obtain refractory material to resist temperatures such as can be obtained by means of the electric arc. High temperature in a furnace possesses several valuable features. It facilitates the reactions taking place between the bath and the flux on the surface. It enables impurities to be removed much more thoroughly, and it renders the metal more fluid, so that better castings can be made.

High efficiency.—The high intrinsic efficiency of the electric furnace is due to the internal generation of the heat which enables the heat losses to be reduced enormously. The heat losses in an arc furnace are due largely to radiation and convection from the exterior of the furnace shell, to conduction through the carbon electrodes, to losses in the water jackets through which the electrodes enter the furnace, and to gas and air leakages through the doors and annular spaces round the electrodes. Losses through air and gas leakage form a large proportion of the total losses and can be minimized by making glands for electrodes and doors for pouring and rabbling as airtight as possible. It may be of interest to give comparative figures for the efficiency of electric and combustion furnaces. In the case of the electric furnace the efficiency is the ratio between the heat required to melt the charge to the heat supplied in units, and in the case of the combustion furnace it is the ratio between the thermal units required to melt the charge to the thermal units of the fuel used. The efficiencies are as follows:

Crucible furnace heated by combustion..	2–3 per cent
Regenerative open hearth furnace ..	20–30 ,,
Electric arc furnace	60–85 ,,

Assuming the overall efficiency of generation of electricity as 10 per cent, the efficiency of the electric furnace based on the thermal units in the fuel used for generation would be 6 to 8·5 per cent. It is therefore better in efficiency than the crucible furnace.

Exclusion of air.—The facility with which air can be excluded from the electric furnace gives it an important advantage, since it enables a neutral or even a reducing atmosphere to be obtained. From the metallurgical point of view this is of great value, as it allows of working without loss of metal due to oxidation of the charge. After these remarks on the general characteristics of the electric furnace, I propose to deal briefly with a few of the points raised in the papers by the six authors.

Connections.—In furnaces up to 6 tons' capacity it is to be noted that most makers in this country are now in practical agreement as to the best system of connections. The authors of five of the six papers are representatives of the makers of the principal types of furnaces now in use in this country, and four of these makers have adopted as their standard arrangement one pair of carbon electrodes above the bath with one or more bottom electrodes embedded in the hearth. The Booth-Hall (Fig. 3, page 248) the Stobie (Fig. 1, page 268) and the Electro-Metals all adopt, as their standard, two-phase current, the two phases being connected to the two upper electrodes and the neutral to the bottom electrode. As a rule the supply to the furnace is in the form of three-phase current, this being transformed to two-phase current by the Scott connection. The Greaves-Etchells furnace (Fig. 3, page 251) employs three-phase current, one limb of the three-phase winding being shorter than the other two to compensate for the lower resistance of the hearth compared with that of the arcs. All four makers are therefore in agreement as to the advantages obtained from the use of a bottom electrode, which has a marked effect in reducing the wear and tear of the roof and sides of the furnace and promotes circulation and uniform heating of the metal in the bath. When the hearth is cold its resistance is large compared with its value at higher temperatures. To overcome this difficulty Mr. Booth adopts an auxiliary electrode, the function of which is simply to act as a means of making contact with the charge. As soon as the temperature of the hearth has been raised by molten metal this auxiliary electrode is withdrawn. Mr. Sahlin tackles the problem in another manner. The furnace which he describes is a development of the Rennerfelt, the distinguishing feature of which is the use of free burning arcs, that is arcs which are struck between two electrodes as opposed to arcs struck between one electrode and the charge or direct arcs as they are styled in some of the papers. When starting his furnace the arcs are first struck between the carbon electrodes. When the charge is melted, one of each pair of electrodes is withdrawn and the arcs are struck between electrode and bath, the current then passing to the bottom electrode in the hearth. In the Greaves-Etchells furnace the hearth is constructed of conductive material which carries a sufficiently heavy current to melt the charge. As pointed out in my introductory remarks, it is more economical to use combustion heat for melting the charge. If a combustion furnace of the regenerative type is worked in conjunction with an electric furnace,

the charge is melted in the combustion furnace and transferred to the electric furnace for the refining process at high temperature. With this system of working, the difficulty of starting from cold does not occur. When the capacity of the furnace exceeds 6 tons a greater number of electrodes must be employed, partly in order to distribute the heating as evenly as possible over the hearth, and partly because the energy which can be concentrated in one arc is limited. Mr. Greaves states that the limit is 8,000 to 9,000 amperes, or 1,300 k.v.a. Mr. Stobie states that long experience has shown that bottom electrodes, whilst essential in small furnaces, are undesirable in large furnaces; on the other hand, the Electro-Metals and Greaves-Etchells furnaces of the larger size retain the bottom electrode, but reduce the current through the hearth as much as possible. The Héroult furnace which is not described in the present series of papers, and which has been used extensively in large sizes, does not employ a bottom electrode. Mr. Bibby in his paper dwells on the necessity of the heat supplied being evenly distributed over the bath, and describes the system adopted in the four-electrode furnace, which is suited for capacities up to 30 tons. In order to provide for equal generation of heat, four equal phases are required, and by means of vector diagrams Mr. Bibby works out the proportion of the windings necessary to distribute the current equally along all the paths between the various electrodes. Between diagonal electrodes a higher voltage is naturally required than between any two electrodes forming the sides of the square, so as to keep the current along all the paths open as uniform as possible. In connection with the furnaces used for the manufacture of pig iron, Mr. Bibby shows in Figs. 3, 5 and 7, the necessary connections and proportions of the transformer windings for furnaces with 4, 6 and 8 electrodes.

Arc phenomena.—Mr. Stobie makes some very interesting observations in this connection. He states that the arc proper is not the only source of heating, but that a flame of carbonaceous gas spreads out from each electrode. Efforts to control the direction of this flame have been made, by him, these being based on the use of a magnetic field, which as is well known has the power to blow an arc or flame in the desired direction. The use of a strong external continuous magnetic field did not show decisive results, but the correct disposition of the leads carrying current to the electrodes so as to cause the magnetic fields coincident with certain arcs to blow these arcs down on to the charge, enables important advantages to be obtained, amongst these being increase in speed of melting and reduction in burning away of furnace lining. Mr. Sahlin (Fig. 2, page 2[illegible]) shows how a free burning arc forms a brush which can be directed down on to the charge. In the original Rennerfelt furnace, there are three electrodes, two horizontal connected to the outers of a two-phase supply, and one vertical connected to the neutral. The object of this disposition is to produce a strong fanning action of the arc over the surface of the baths. The magnetic field produced by the currents flowing have a pronounced blowing effect on the flame of the arc.

In the revised type of Rennerfelt furnace, described by Mr. Sahlin, the two electrodes forming one pair are inclined at a fairly acute angle to one another and the inter-repulsion fans out the arc into a brush.

Transformers.—Mr. Mercer in his paper remarks on the importance of the design and construction of the transformer. Transformer makers did not realize in the early days the mechanical strains to which the windings would be subjected, and enormous failures occurred owing to insufficient anchoring. It frequently occurred also that the k.v.a. capacity provided was insufficient. When the charge is melted the power factor is often as high as 0·9, but when starting up with a cold charge the reactance is much higher and the k.v.a. demand is greatly increased; the power factor may be as low as 0·7. If the transformer were designed for a power factor of 0·9, it would be seriously overheated. Mr. Stobie gives a valuable list of the desiderata in a furnace transformer (page 270). He lays special stress on the necessity of anchoring all clamps to the transformer frame and including as much as possible of the total reactance in the transformer itself. He also mentioned a point to which I referred in the discussion on the recent papers on "Testing," viz. the need for an over-potential test which can be easily carried out at an increased frequency. This is of great value in testing the insulation from turn to turn.

Power factor.—It is claimed by some makers of furnaces that they can work at almost unity power factor. This, from the point of view of good commercial operation, does not appear to be desirable. In most types of arc furnaces serious current surges are found to occur during the melting period, and to provide against these some reactance is necessary. In practice this reactance is usually divided between the leads and the transformer and no additional reactance in the shape of choking coils is called for; in fact, unless the disposition of the leads is such as to reduce the reactance as far as possible, there is a tendency for this to be too high. By interleaving the conductors carrying the heavy low-tension currents from the transformers to the electrodes, the reactance can be kept within reasonable limits. With furnaces in which the hearth forms part of the furnace circuit, the resistance of this, which is a steady quantity, prevents the short-circuit current rising to abnormal values. Mr. Stobie states that he aims at 20 per cent impedance voltage when the electrodes are short-circuited, and under such conditions obtains a power factor varying between 0·84 and 0·93 on the furnace itself. In the case of a dead short-circuit the power factor may be reduced momentarily to 0·4.

Electrodes.—Up to the present, carbon has been found to be the only practicable material for the electrodes. Of the two classes of carbon, graphitic possesses the advantage of being a better conductor than amorphous; consequently smaller diameter electrodes can be used if graphite is employed. This means smaller holes in the furnace roof, smaller water jackets, with less waste of heat and less trouble from the skin effect which is a serious factor with large diameter carbons. Further, with a reduction in the size of the electrodes the leakage

of gases from the furnace can be diminished. One of the most valuable features of the electric furnace is the possibility of producing a neutral or reducing atmosphere by the exclusion of air, and this depends, naturally, on rendering all the openings in the furnace as air-tight as possible. On page 273 Mr. Stobie gives an interesting series of figures showing the effect on the electrodes, both inside and outside the furnaces. From an examination of these, the need for making air-tight joints round the electrodes is very evident. The air gland or economizer, as Mr. Stobie calls it, is a very simple but effective device. It not only facilitates the formation of a reducing atmosphere, but increases the efficiency of the furnace by cutting down the loss of heat due to the escape of hot gases. On page 275 a list of the advantages obtained by this device are given and, in my opinion, these claims are amply justified.

Circulation of the bath.—Mr. Stobie's remarks in this connection are somewhat revolutionary, but they appear to be based on extensive experiments with mercury baths. It has been generally accepted, hitherto, that the electromagnetic effect of the currents passing through the molten metal in the bath is to produce a motion of the metal. In the induction type of furnace the current through the bath reaches a much higher density than in the arc type, owing to the heat being generated in the bath itself instead of principally in the arc, and with furnaces of this type the frequency is usually kept as low as possible to prevent the circulation becoming so violent as to scour the sides and bottom of the hearth. It is, therefore, natural to expect some movement of the metal in the arc type where currents flow through the molten baths, which though not as large as in the induction furnaces are still of considerable size.

Furnaces for other purposes than melting steel.—The papers deal almost entirely with furnaces for melting and refining steel, and at the present time this is the purpose to which the greatest number of electric furnaces, of sizes dealing with ½ ton and upwards, have been applied. The electric furnace is, however, capable of doing good work in many other directions. Mr. Greaves mentions a few of these such as the reheating, annealing or melting of metals which have a low melting temperature, and states that for such work the resistance type of furnace is the most suitable. Up to 1,000° C. he recommends a heating element of an alloy of nickel chromium. A considerable number of small furnaces of this type are in use, more particularly in laboratories. One interesting furnace of this kind which I have come across is designed to heat a bath of fused salt for the hardening of tools, dies, etc. The temperature necessary for this process is accurately adjusted by taking advantage of the fact that the decalescent point of steel is also the point at which it becomes non-magnetic. By means of a sensitive galvanometer connected in circuit with a special coil on the furnace, it can be determined within close limits. For temperatures above 1,000° C. the resistance material is usually some form of carbon, but other highly refractory materials are also used for the purpose. It is an easy matter to render a resistance furnace perfectly gas-tight, which is a desirable feature when employed in melting such material as brass, since it avoids the loss of zinc through vaporization. Mr. Sahlin outlines (page 267) a proposal to construct what may be called a heat reflector, which may be suspended over a hearth containing the material to be treated. The heat reflector contains a free burning arc the radiant heat from which is directed down on the hearth. If the material of which this heat reflector is constructed is sufficiently refractory to withstand the heat and flame from the arc, the proposal would seem to be a useful one, but my experience with free burning arcs has been that the roof suffers more than any other part of the furnace shell. Consequently, instead of one heat reflector serving several hearths, it would be necessary to have several reflectors for each hearth. Arc furnaces are used for many other purposes beyond the treatment of steel. Among these may be mentioned the production of phosphorus. It may be of interest to members to know that the first furnace for the production of phosphorus was designed and constructed by Mr. Thomas Parker of Wolverhampton and furnaces built on these lines have during the war turned out enormous quantities of phosphorus. The original furnace was designed for use with direct current but at the present time the magnitude of the currents employed necessitates the use of alternating current. Mr. Mercer in his paper gives a large number of tables showing the numbers of furnaces in use and the results obtained in working, and this information is valuable to users of furnaces.

Mr. W. Wilson : I should like to ask Mr. Moffett whether there is not a further advantage of the electric furnace in that it can treat a wider selection of iron ores than one depending on combustion. A number of years ago I was acquainted with attempts that were being made to reduce magnetite iron-sand, which was present in a certain deposit in enormous quantities and in a state of great purity. All the attempts were then futile owing to the finely divided state of the ore, which clogged the ordinary type of furnace. Now this defect should be no detriment whatever to an apparatus that does not depend upon combustion for its action, and I would suggest that this is a real advantage possessed by the electric furnace. No mention has hitherto been made of the use of electricity for the fixation of atmospheric nitrogen, in the production of nitrates for use as fertilizers, etc. This type of furnace seems to me especially important in that it should offer itself as a useful load for bulk-supply schemes. These furnaces require very little attention, and hence can be installed in remote localities where, for example, a large hydro-electric undertaking might be situated. Such an establishment frequently charges for its current at the rate of so much per kilowatt per annum of maximum demand ; so that a customer would have a large amount of energy on his hands during times of light load, which would be going to waste as far as he was concerned. Now if such a furnace as this is capable of being started up after the lighting load has died down at night, and run until the peak load begins in the morning, and then shut down until the off time sets in again, it should provide a very useful way of using up the surplus current. I should like to ask if this

furnace is adapted for intermittent running of this nature, as it would then be a valuable asset to engineers who are projecting large supply undertakings, and are on the look-out for prospective loads.

Mr. W. F. Whittaker: I should be glad to learn what is the best method of creating a long brush effect or downward deflection of the arc flame when using three-phase current, also for extending a two-phase flame, obtained by arranging the electrodes in use with the two-phase electrodes horizontally, and the neutral vertically. The furnace I am experimenting with is for use with an ore having very low conductivity, which has to be volatilized, leaving only a small amount of slag, so that the usual steel furnace form, with well bottom, and neutral below the ore, is not at all suitable, and as it is desirable to keep free air out of the furnace, a hot air blowing effect cannot be used. Mr. Stobie mentions the matter but does not give much information, possibly because it does not appear to be of great importance in steel smelting, although to me it is very vital and I should be glad to receive any information that would assist me.

Dr. G. Kapp: With reference to Mr. Wilson's remarks, a nitrogen furnace working with three-phase current of which I have had some experience would be able to fill up gaps in the load. The gaps must, however, not be of too short a duration. When started up cold the furnace requires some time to get into a steady working condition. If the gap in the general load on the generating station were only a matter of 3 or 4 hours it would hardly pay to work the furnace for such a short time, since the yield would be too small in comparison with the energy used because all the heat contained in the furnace after stopping is necessarily a dead loss. There is also the question of cost of labour, which must include payment for a large proportion of time when the furnace is heating up. If, however, we had a plant which supplied consumers who took most of the power during, say, 12 hours in the day and set nearly all the power free for furnace use during the whole of the rest of the time during the night, then the suggestion made by Mr. Wilson might become a commercial proposition.

Mr J. Bibby *(in reply, communicated)*: Mr. Burnand has raised the question of the effect of electric currents flowing through the metal. I do not think any electric furnace makers believe in the superstition with which he charges them. It is immaterial how the currents flow through the metal. Practically the whole of the heat generated in the furnace is at the arcs, and the main consideration as far as heat generation is concerned is to have equal potentials between the electrodes and the bath. It does not matter what potential there is between the upper electrodes. In the system described, the pressure drop is the same between each electrode and the bath, so that if the currents are the same the dissipation of energy will be the same in every arc.

Mr. Burnand has also overlooked the fact that the resistance between any two electrodes is equal to the resistance of two arcs, and it does not matter where the electrodes are located, the resistance of the metal is negligible. In the four-phase system described, the bath forms a star connection for the four phases and the resistance in each phase is equal to one arc, which is precisely what the transformer system gives.

Mr. R. G. Mercer *(in reply, communicated)*: This discussion on electric steel furnaces has been not only very interesting but very instructive, and tempts me to depart from the principle on which I started out, by, on the one hand, giving particulars regarding the various shortcomings in some of the designs of electric furnace makers, and, on the other hand, describing how these shortcomings due in a large measure to faulty design, with contributory bad working conditions with furnaces of certain types, occur; in other words, that I should amplify the details given in the tables in my paper.

Mr. Harbord says that all the furnaces, so far as steel manufacture is concerned, are very similar and chiefly vary in the electrical connections, having small advantages over each other so far as mechanical details are concerned. This is true to a certain extent, for while a furnace maker "A" may have a fairly good tilting arrangement his electrode raising and lowering gear may be by no means all that can be desired, and vice versa with regard to furnace maker "B." Furnace maker "C" may have defects in both, while furnace maker "D" may be wanting in both these defects. It is features such as these that largely account for the satisfactory operation or otherwise of an electric steel furnace. The question of human element does not come in here since all the precautions which the operator can humanly take may be quite in vain in face of bad or inferior mechanical design. These are two of the most serious causes of electric furnace breakdowns, quite apart from failure of water supply, with consequent breakdown of the water-cooled collars round the electrode entrance through the roof; quite apart also from incidental troubles and delays due to the breaking off of electrodes, especially of the amorphous type, in the furnace; and quite apart also from hearth-bottom and roof troubles; for this reason, that any failure of the tilting arrangement may cause not only serious delays but also loss due to the freezing of molten steel just when it is ready for teeming. In the same way the failure of the electrode raising and lowering gear, when we may assume there is a bath, may involve the pouring off of the molten metal to avoid freezing, with resulting loss.

Dealing with the electrical system of connections, it is in my opinion a moot point whether a furnace having a bottom connection is as good as or better than one without. The maker of the furnace with a bottom connection claims that he gets a rotating movement in his molten steel, which I understand it is claimed enables a user to make, say, a tungsten steel without rabbling. I entirely disagree with such a claim and do not think any electric furnace, whether with a bottom connection or not, will make a tungsten steel without rabbling. Certain speakers have pointed out that if we could apply the heat from the bottom, instead of from the top through the bottom, we could get this circulation; but I think it is obvious that by applying heat only at the top, and assuming that we obtain a certain amount of heat through the bottom, we shall certainly not get the circulation or rotation of the molten steel that is claimed, and it is for want of

this circulation or rotation that rabbling has to be resorted to.

Mr. Ellis asks whether a 12-inch graphite electrode cannot deliver more than 11,000 amperes. As stated in my paper, I certainly do not recommend a higher current density than 100 amperes per square inch for graphite electrodes, and in the case of amorphous carbon I do not think that under present conditions the current density should be more than 25 amperes per square inch. As explained in my paper, due to the absence of a reliable electrode economizer on a furnace of the gallows-arm type, if the current density, especially in the case of amorphous carbon, is increased beyond these limits oxidization occurs, with a resulting decreased diameter of the electrode, thereby increasing the current density at that point, with the result that we get not only a large amount of heating due to conduction from the furnace backwards, but also, owing to the decreasing diameter of the electrode, a further heating up due to the higher current density. The result is that the trouble becomes accentuated. The furnace user is only too well aware what may happen due to the above, especially in the case of amorphous carbons of large diameters, for he experiences breakages of carbons inside the furnace, with consequent great delays in trying to get out a large lump of electrode in molten metal through a small charging door.

The question of transformers has been very fully dealt with and I think it is only necessary to say that furnace users and makers have learned from past experience that the transformer capacity must be considerably increased in order to get reliable and continuous operation, and that transformer makers are to-day well aware of the extremely hard conditions to which a transformer has to stand up, especially during the melting-down stages. Such substantial improvements have been made in the general design, especially on the mechanical side, that to-day a transformer can generally be looked upon as quite reliable, provided that ordinary care is taken not only of the transformer itself but of the auxiliary electrical plant controlling it.

Mr. Campbell states that in very large works the performance of the furnace is not so good as it is in small works, and he attributes this largely to the traffic, cranes, etc. I do not agree with this, for I have data where the performance of furnaces in certain large works in this country is very much better than, I will say, a single furnace in a small works. There are other delays than those due to traffic and cranes. I have already referred to delays due to failures of tilting or electrode-raising gear; there are delays due to roof replacements, failure of water supply, and, apart from the transformer, hearth bottom troubles, especially in furnaces having a bottom connection.

Sir Robert Hadfield is quite correct in stating that the low current consumption of certain electric furnaces mentioned by Mr. Mordey is due to the case in question being purely a melting proposition, the furnaces being used solely for melting steel for steel castings.

Colonel Carnegie does not state what class of steel was being made, or whether it was from the cold scrap, but we have nothing to compare with those results in this country. It would have been of interest to me to know over what period he was getting 400 tons per day.

I entirely agree with Mr. Ridge's suggestion that co-operation between the electrical, metallurgical and constructional sides of the electric furnace would give better operating results. If the furnace is of good mechanical design and the general lay-out, including the electrical portion, is installed properly, the user has nothing to do but to concentrate on the making of steel, which, as Mr. Ashdown states, requires the greatest care and attention. It is very largely owing to failures, due either to mechanical design or neglected inspection of the electrical end, the failure of water supply and troubles with electrodes, that current consumptions as high as 1,100 units per ton mentioned by Mr. Mordey are recorded in the production of steel. Such delays of course mean that the furnace is temporarily shut down and a large amount of current has to be used in reheating. In addition to the above, a large amount of current can be saved by the adoption of a reliable electrode economizer such as that described in Mr. Stobie's paper. All my records go to show that with such an economizer not only is the current consumption per ton of steel in the ladle appreciably reduced, but a large saving is effected in the electrode consumption, the heat period is shortened with consequent increased output, and the life of the roof is, generally speaking, longer. Too much attention in my opinion cannot be given to this side of the question.

Mr. Parker has dealt very fully with Mr. Mordey's remarks regarding the induction furnace and I agree with all he says. It should also be remembered that at the present time the power factor of the induction furnace is extremely low, unless the frequency is as low as 12½ periods when it is claimed that the power is as high as 65 to 70 per cent.

Mr. Brown states that while various figures are quoted as to the power required to produce a ton of steel, the composition of the steel has not been mentioned. In the tables in my paper I have given as nearly as possible this information, and it will be noted that under the heading "Class of Steel" letters "HS" (high-speed steel), "Cgs" (castings), NiCr (nickel chrome), etc., are mentioned, in order to convey what class of steel each furnace is making. There is not a great difference in the consumption so far as alloy steels are concerned, but there is a difference between these and steel for castings. Furthermore, furnaces of the same size are shown making the same class of steel over periods ranging from one to five or six months, and under the heading "Delays" is shown the number of days lost through all causes. I think it may be accepted that in making, say, NiCr steel NiCr scrap would be used, but I did not wish when writing my paper to do more than generalize, so that particular furnaces could not be recognized. The claim that furnaces having a bottom connection give effective circulation of the bath of molten metal is, I think, very much exaggerated, and I certainly do not believe that we could make, say, tungsten steel relying on this alleged circulation without rabbling.

Mr. Dawson deals with the question as to whether a higher voltage is desirable on the low-tension side. By increasing the voltage at the arc we of course pull a

longer arc and the refractories would in consequence suffer. It might be advisable during the melting-down stage but it should be reduced when the bath has been obtained, the arc then being muffled in the slag thereby helping to protect the refractories. Mr. Dawson's remarks regarding failures of economizers are quite true so far as furnaces of the gallows-arm type are generally concerned.

I agree with Mr. Sillars that it is necessary to allow gases to escape during certain periods; in fact it is very hard to stop them coming out through the tops of the charging doors, but this is quite different from allowing these gases to escape through the roof, to which I am entirely opposed. With regard to furnaces having a bottom connection I am quite satisfied that a new bottom has to be most carefully put in and with the best possible refractories.

Mr. Sprague says that 12-inch graphite electrodes are being used in America to carry 15,000 to 20,000 amperes. This of course increases the current density very materially and I think it should not be more than 100 amperes per square inch; a higher current density results in heating and also possible troubles where inferior electrode joints are concerned.

Mr. Travis is of opinion that no reference has been made to the scope of electric furnaces in connection with the manufacture of steel castings, but the tables in my paper show that there are a large number of furnaces in this country making this class of steel. It is well-known that steel castings produced from the electric furnace are extremely good, and there is no doubt that there is scope for electric furnaces for this class of work.

If as a result of these papers and the discussion the makers of electric furnaces on the one hand eradicate the weak features as far as possible with a view to putting in the users' hands a reliable apparatus properly installed, and if the user on the other hand gives the attention to it which any useful tool should receive, there is not the slightest doubt in my mind that very much more satisfactory results will be obtained and that those who now condemn electric furnaces will be convinced they can turn out good steel.

Mr. V. Stobie (*in reply, communicated*): It would appear that Mr. Harbord has considered the electric furnace in its relation solely to structural steels; but, even so, I would point out that modern electric furnace practice is not at the stage where the old beliefs he expresses applied. If Mr. Harbord means that all types of arc electric furnaces are similar metallurgically in so far as they all melt by means of the electric arc, one is sure to agree; but the differences in electrical and, more especially, mechanical details between types not only enable but directly cause alterations in the metallurgical conditions. Take one item alone: the addition to the roof of the economizers described in my paper. In this case a furnace is changed from one having free air inside to one having such a reducing atmosphere that it will actually deposit free carbon on the charge being melted. The purely metallurgical change brought about by this single feature is considerable. Another early view expressed by Mr. Harbord and one which is generally, but erroneously, held is that the electrode holes in the roof of a furnace are of necessity a source of weakness. I am more able to speak of my own furnaces than of others, but I do not know a Stobie furnace wherein the roof is not thicker at the electrode holes than elsewhere after a campaign. This, again, is due to the *cul-de-sac* formed by the economizers and also to the disposition of the water coolers inside the electrode holes. There are several types of arc furnaces having no electrode holes in the roof. In such furnaces the electrodes are brought in through the side walls. It is known that the roofs of all such furnaces give in much more rapidly than the normal type of furnaces with electrodes through the roof. The vertical electrodes are a protection to the roof inasmuch as they shield the latter from much direct radiation from the arcs.

Dr. Stead's remarks are helpful in recalling to metallurgists that a steel process of to-day is not necessarily for to-morrow. I would place the suggestion of Mr. Harbord that the electric furnace should be used in conjunction with Bessemer plant to produce steel equal to the best open hearth side by side with Dr. Stead's submission that the now very high cost of pig metal probably dooms for ever the Bessemer process. Several Bessemer steelworks have, in fact, ceased working and have been dismantled in the last year or two on account of the passing of the Bessemer process; therefore I suggest that, similarly, in repeating the opinion he expressed on electric furnaces before the war Mr. Harbord has given insufficient weight to post-war conditions.

Mr. Ellis doubtless does not suggest that any words of mine are intended to propose that switchgear or any other electrical apparatus included in a furnace installation should not receive as thorough consideration as the transformers. As I have not any direct personal knowledge of the failure in operation of any furnace switchgear I cannot agree with the suggestion that such apparatus is often liable to be a source of trouble. I do not think transformer makers should, as is suggested by Mr. Ellis, be encouraged to suit themselves in the designs and specifications of furnace transformers. My own experience is that I have yet to hear of a transformer built to the general specification I give in my paper, and which I require embodying in transformers for Stobie furnaces, failing through any limitations so imposed. In fact only one transformer so built has ever failed, and the failure was due to a liberty taken *sub rosa* by the maker and admitted by him later to have been wrong. Unfortunately, it is not possible to do as Mr. Ellis suggests and fix a final kilovolt-ampere requirement for each size of furnace. There is no such thing as a definite demand of energy fixed by the tonnage of steel. Any quantity of power up to thousands of kilowatts can be taken by a single ton of steel, so it will always remain for the furnace designer to decide from the output required from the furnace what arbitrary kilovolt-amperes are to be adopted for the installation. This being so, I think transformer makers who, like Mr. Ellis and his colleague Mr. Thompson, have done much to help along the electric steel plant industry, will admit it to be an essential requirement of the furnace designer that the transformers should conform to his general limits of specification rather

than they should be totally independent designs having no special bearing on the furnace designer's lay-out and experience. My limitation of current density to 1,250 amperes per square inch in a furnace transformer is criticized by Mr. Ellis as importing nothing unless the maximum continuous overload is specified. Can any transformer maker state what is the maximum continuous overload of a transformer ? Until a definition very different from the one usually given is available, I prefer to adhere to what I know is a very liberal current density for windings composed of suitable conductors suitably wound, and to limit the temperature-rise both in the windings and the oil to a reasonable figure after continuous full *nominal* load run. Nothing can be safer as a basis. I agree with Mr. Ellis that it is of no use attaching a host of bracings to transformers unless there is a definite and substantial reason for each one. All bracings, it should be remembered, are not for helping the windings to resist stresses ; some are for supporting them in position to avoid dislocation of their magnetic centres after shrinkage of insulation, and some which may be unnecessary in one design of transformer may be required in another not through any fault in the latter. As regards the taping of the low-tension windings, Mr. Ellis rightly points out that the oil will abstract heat from bare copper more quickly than from taped copper. By limiting the current density to 1,250 amperes per square inch, as specified in my paper, the taping is found to be totally unaffected by heat after considerably long runs. There is another great advantage in taping the low-tension windings and one which I have not mentioned in my paper, viz. the considerable reduction in sludging of the oil due to its protection from the copper.

The letter which Sir Robert Hadfield read from M. Girod is interesting in regard to the development of output of electric steels at the Girod works. Fortunately for M. Girod, his current is generated from " white fuel " and therefore he is not troubled with coal costs. If we in this country were equally favoured, our production of electric steel would be much greater, as there is no doubt that some buyers of steel will purchase pen-hearth steel for many purposes where electric steel is known to be better because of the extra cost of the latter over the already high-priced open-hearth tonnage steel. In his letter M. Girod claims to have been the originator of the conductive hearth. In the course of correspondence in an American technical periodical some years ago M. Girod made the same claim, and it was contended in the same periodical by M. Héroult who gave the date and (I believe) the number of a Belgian patent he took out on a conductive hearth prior to M. Girod's patent. I mention this merely to keep history clear. Sir Robert Hadfield's suggestion of a difference between the heat of ordinary combustion and that obtained from electrical energy is interesting but, quite apart from an unlikely physical difference, I think the method of applying the heat accounts for the lowering or total absence of " inclusions " in electric steel and the resulting higher transverse tests. At my own steelworks I have made nickel-chrome air-vessel steel in which neither the large armament firm for whom it has been made nor the Government torpedo factory laboratories have been able to detect even a trace of inclusions.

Mr. Carnegie's figures are interesting and should be revised to date. Replying to his query on the subject of the possibility of electrically converting ore direct into steel, I do not consider the suggestion practicable commercially. The slags resulting from the reduction of iron ore would always be a source of trouble, not only chemically but also mechanically. Just as it is most favourable to run a blast furnace, mixer and open-hearth train for cheap production of ordinary steel, so will it probably pay to use specialized furnaces for each step between iron ore and finished electric steel.

I would inform Mr. Dixon that I first made electric steel in 1910 and that I have continued making it since then and have had for several years the largest electric furnace at work in the country. I put my figures forward, therefore, as the practical results obtained at my own steelworks to-day. They are also confirmed by other works operating Stobie furnaces.

Mr. Saniter is undoubtedly correct in saying that electric steel cannot compete in price with structural steel made in the open-hearth furnace ; but tube steel made in the electric furnace is stated by users to be much more regular and more capable of withstanding the punishment meted out to the steel in the manufacture of weldless tubes than does open-hearth tube steel, yet that is one of the steels which should give the open hearth a good comparison. During the war the Air Board always preferred electrically-made steels to open-hearth product for their highest tensile specifications because they obtained much better all-round results with such steels.

Mr. Mordey's remarks on the wastage of electrodes are to the point. Until I devised the Stobie economizer in 1916 there was no possibility of avoiding the serious wastage of electrodes and heat that resulted from the rush of flames out of the roof through the electrode holes. Many methods had been tried previously, and I had studied the subject from my earliest work on electric furnaces in 1910. The economizer seems to-day an obvious remedy ; but until its advent all attempts to seal the roof consisted of ganister, clay or similar substances thrown on the roof round the electrode.

I believe Mr. Parker's *exposé* of the running of the first induction furnace in the country is the only description available of that occasion, and it is a valuable contribution to the history of electric furnaces.

Replying to Mr. G. M. Brown, the consumption of electrodes in a furnace is undoubtedly related to, inter alia, the sectional area of the electrodes. There is a correct size of electrode for each furnace. If too small a diameter is used, the electrode will get red hot above the furnace due to too high a current density, and may even break due to that cause. The red hot electrode will spoil copper terminals and will in general obstruct work. If the electrode is of too large a diameter there will be a high consumption due to the exposure of too great a surface to burning inside the furnace. The economies in current and electrode resulting from the use of efficient economizers, for which Mr. Brown asks, are

given below. I also add the saving in refractories and time required per heat:—

	Stobie furnace.	Rest of furnace.
Current	15 per cent	20 per cent
Electrodes	75 ,,	60 ,,
Refractories	20 ,,	40 ,,
Time	20 ,,	30 ,,

The comparison is with ordinary good practice without Stobie economizers and not with bad practice. As Mr. Brown emphasizes, claims by some furnace designers that their furnace gives circulation to the molten metal cannot be supported in theory, and the experiments described in my paper conclusively disprove the fallacy. The rigidity of electrode holders is most important. I adopted a rigid bridge construction in 1913 and have always built furnaces so equipped. I cannot understand why other makers adhere to the original gallows-arm carriers notwithstanding the repeated failures from that source. They are invariably the cause of heavy breakages of electrodes and unbalanced stresses in the furnace structure.

Mr. Toy complains of the royalty charged by furnace makers. I agree with him that it should not be unreasonable. I would go further and say that no royalty should be charged if the patentee can only show a difference in electrical connections between his product and another. The only occasion on which a royalty should be paid is on substantial economies by the use of some distinct innovation incorporated in a furnace.

Mr. Dawson says that furnace makers should try to provide a really effective economizer and that although he has seen many, he has never yet found one that is successful. As this leads one to conclude that Mr. Dawson speaks with a knowledge of the device I have described, I must reply that Mr. Dawson has not given an opportunity for a supervised run on his plant with the economizer. In fact he is aware that refusal to have a demonstration is not the best test of the apparatus. On the 100,000 tons of electric steel turned out from one works during the war, at least £2 per ton would have been saved by the use of the economizers. A somewhat modified steel process accompanies the use of exhaust economizers, and this is so material that my own works turned out less steel on first using the economizers than they had previously done. On probing the matter, the solution became evident and the righted process increased the original speed by 20 to 30 per cent., over 1,000 tons of clean ingots being obtained in a month with 10- to 11-ton charges. Contrary to Mr. Dawson's suggestion, an economizer such as described in my paper does not need repairs after every few days. Apart from the occasional replacing of a piece of [illegible] tube, others and I have had Stobie economizers running year in and year out, giving them a very little attention wherever a furnace is down for repairs. A glance at Fig. 9 will show there is nothing to go wrong.

Experience shows that it is not necessary, as Mr. Dillon suggests, to have holes in an electric furnace to let out excess heat which might otherwise fuse the mouth of the melting chamber. On the contrary, the rushing of flame past furnace brickwork is a powerful abrading agent and very rapidly wears away silica brickwork. The producing of heat in the furnace and then letting it out with the idea of avoiding too high a heat in the furnace is not economical. Either the heat is not wanted, or it should be absorbed.

The difference in running costs of furnaces noted by Mr. Pyne may be due to difference in methods of calculation. It is probable that one firm gave net material and labour costs and that the other gave costs completed to the last farthing. Automatic control is, as Mr. Pyne suggests, of invaluable service and should always be adopted except in special cases.

I would commend Mr. Service's remarks about the superiority of electric steel over open-hearth steel to those who, unlike him, have not had considerable experience with both steels. Sulphur prints from the sectioned trepanned cores of the steel made at my works to which Mr. Service refers revealed only a monotonous, unmarked structure such as is believed by many metallurgists to be unobtainable.

The furnace referred to by Mr. Imbery is one requiring not only high voltage but extra high frequency. Such frequency can only usefully be obtained by installing discharge condensers or very special rotating machinery. In either case, the cost per kilowatt of capacity would be greatly in advance of the cost of arc furnaces and the plant cannot offer the chemical advantages of arcs.

Mr. Sprague's interesting contribution on graphite electrodes brings out the points I made in my paper in regard to the fault so often made of comparing direct current carried by an electrode with the loading up of the same electrode on an alternating-current supply. The current density of the outer portions of the sectional area of an electrode carrying an alternating-current supply is much greater than the average density, and therefore the average carrying capacity of an electrode carrying alternating current must be less than that of one carrying direct current if the current density of the outer sections is not to exceed the current density of the electrode carrying direct current. In very round figures, a 12-inch round electrode will allow an average alternating current density of half that of a similar electrode carrying direct current.

Mr. Travis's addendum to Mr. Greaves's paper is interesting to other furnace designers like myself for the original ideas it contains. Mr. Booth's statement criticized by Mr. Travis, concerning two sets of grids in the hearth being electrically insulated from each other, is undoubtedly correct in substance, as only highly-heated portions of the hearth are good conductors and it is easy to arrange for a long and comparatively cold length of hearth between the two grids. Mr. Travis is, fortunately, not correct in suggesting a disadvantage in my furnaces Figs. 2 and 3 from the electrodes not being independent. On the contrary, the two arcs in series form a most effective resistance buffer which prevents fluctuations reaching high values such as occur in the single arc per phase system adopted in Greaves-Etchells furnaces. He is also wrong in suggesting that special means of electrode regulation is required. Stobie furnaces are controlled by exactly the same makes and systems of automatic controllers as his and other furnaces. The only difference in regulation is that any fluctuation which has not been

prevented by the buffer action of the two arcs arranged in series is taken in hand by the motors operating the two electrodes in series and is rectified in half the time required by single-arc-per-phase furnaces. Mr. Travis suggests that bottom electrodes are not, as I stated, very undesirable in large furnaces, and that they have been used for all sizes of furnaces. There is no furnace larger than 7 tons in this or any other country working on uncooled hearth connections, and as Mr. Travis does not use the water-cooled type of bottom connection in the Greaves-Etchells furnace, I presume he refers to the kind used in this country. Even on Mr. Travis's own showing, no large furnace could long be successfully run with such hearth connections. He says 500 amperes per square foot of effective hearth surface is safe. A 12-ton furnace on single-arc-per-phase running would have a current flow of some 15,000 amperes. This would necessitate an "effective hearth area," which must commence below the bath level, of 30 square feet. Should all portions of such surface not be absolutely equidistant from the bottom electrode, and we all know they never can be, then this huge current will mainly flow through the narrow portions. Such portions will become much more highly heated and therefore their conductivity still further increased. The results are cumulative, and disaster must result sooner or later. Going a little further than Mr. Travis has done into the question of bottom heating for large furnaces, and taking Mr. Travis's statement that 8 to 10 per cent of the total energy supplied to his furnace is absorbed in the hearth, one finds that if he built a 12-ton furnace 240 kw. to 300 kw. per hour would be at times absorbed by the hearth. This waste is, of course, additional to the high heat imparted to the hearth by the molten steel. The heat developed in any part of the hearth by this absorption of energy will be proportional to the voltage drop across such part. The dolomite mixture forming the hearth has a very high resistivity when below red heat and it becomes increasingly conductive in a much greater ratio than its increase in heat. It results therefrom that at a steel-melting temperature the dolomite is of good conductivity. Assuming the hearth to be 10 inches thick between the bottom electrode and the surface of the crucible, there would be, in normal working, roughly 1 inch thickness of good conductivity, 2 inches of mediocre conductivity, 2 inches of poor conductivity, 2 inches of bad conductivity and 3 inches of very high resistivity. The voltage drop at full load across the hearth bottom would be relegated, as to 50 per cent in the bottom 3 inches, as to 25 per cent in the next 2 inches, and the balance variably in the upper layers of the hearth. What is the result? 120 to 150 kw. would be wasted 8 to 10 inches away from the bath; 60 to 75 kw. absorbed 6 to 8 inches away; and 60 to 75 kw. absorbed mainly 2 to 6 inches away from the molten steel bath. In other words, the main heat resulting from the absorption of energy by the furnace hearth is dissipated in the most distant parts of the hearth from the steel bath, i.e. just those parts which it is most necessary to keep cool. I have not been able to find the specified results of using Stobie economizers which Mr. Travis states Mr. Mercer gives in his paper. If, however, Mr. Travis has considered the lowest consumptions of electrode given in the tables in Mr. Mercer's paper to relate to Stobie furnaces he is quite correct. Amongst the others in those tables are the Greaves-Etchells furnaces. Had the latter given the low consumptions which Mr. Travis would claim for them, they would of course have figured in those official tables in the positions occupied by Stobie furnaces. Mr. Travis says he has now abandoned the bath-circulation theory. If he will also throw out the convection-current fallacy, advancement will be much quicker. Anyone who believes he can make successfully an alloy steel such as described by Mr. Travis without vigorous rabbling of the bath has either never made such a steel or has not concerned himself with the analysis afterwards. No heat imparted by the hearth connections to the lower layers of molten steel could possibly make those bottom layers hotter than the top layers which are next the slag; therefore, how can Mr. Travis bring himself to suggest that 8 to 10 per cent of the total energy, even if it were all imparted to the steel next the hearth, should cause such steel to rise by expansion and displace the steel at the top of the bath which is heated and expanded by 90 per cent of the total energy? It is not on such unsupportable theories that the electric steel industry can thrive; much better admit there is no more circulation in the electric furnace than in the open hearth furnace and encourage rabbling for all one is worth.

Mr. Howard raises some interesting points as regards the working of large furnaces such as Figs. 2 and 3 in my paper. The fear he expresses of single-phase working is no greater by those connections than when using ordinary three-phase three-wire connections to furnaces, as the three phases of the high-tension side are permanently coupled up. In the case of Fig. 2, if one of the low-tension phases is put out of commission, the high-tension is not so unbalanced as if one low-tension phase of a three-phase three-electrode furnace were out of commission. With the connections as in Fig. 3, the out-of-balance with one low-tension phase out is exactly the same as in a three-phase three-electrode furnace. I regret Mr. Howard does not mention the four points he does not like in my description of suitable transformers. As regards my preference for as much as possible of the circuit reactance being embodied in the transformers, the reason is that should a short-circuit happen in or near the transformers they are more able to resist disruption. Of course, if the short-circuit is on the high-tension side there is not much gained. I have not experienced any higher cost of furnace transformers due to the reactances I specify. With the other limits of specification I fix there is no cause for increased price. I do not care for reactance iron on the low-tension leads. These latter sometimes get hot when a furnace is pressed, and a local addition of heat by reactance iron in the vicinity should be avoided. The dividing of the primaries in the middle for balancing voltage alterations whilst preserving the symmetry of the windings and the end reinforcement of insulation does not increase the switchgear sufficient to cause any important increase in price, nor does it appreciably complicate the connections. It entails running eight leads from the

transformer to the selector switch instead of four. But all this is insignificant compared with the electrical advantages gained. There is no change in the main switch. I am glad to inform Mr. Howard in answer to his doubt as to whether such connections can be made on a selector gear operating under oil that I have several installations on hand at present wherein that is being done just as easily and as free from complication as if unsymmetrical windings were being dealt with.

Replying to Mr. Crapper's suggestion, arising out of my paper, that engineers accustomed to the design of transformers should settle such matters as reactance, I should consult them as I would a tailor in regard to the cloth for a suit. In other words their suggestions are always to be warmly appreciated, but the furnace designer has the whole of the electrical lay-out in hand and knows, or should know, what total reactance he is seeking in his circuits. The lay-out of furnace circuits such as in 3,000 k.v.a. furnaces is not merely a matter of reactance calculations: it is to a great extent dependent on magnetic materials all around the installation which have no definitely calculable values. I would place actual experience in furnace lay-outs as the first guide, and consider a few calculations for calibrating the designer's mind as a necessary tonic. As a proof of this I would call attention to the ascertained power factors of large Stobie furnaces given in my paper, and against that mention a case of which I have recently heard where eminent consulting electrical engineers have been called in to discover why another make of large furnace only gave a power factor of about 0·3 and have not succeeded in putting the lay-out in order. This case is known to several furnace transformer makers. As Mr. Crapper suggests, the information concerning wave-form results from oscillograms. These oscillograms relate to the characteristics of arcs supplied with energy of sinusoidal wave-form at unity power factor. The statement which Mr. Crapper says he does not understand is, undoubtedly, not clearly expressed. I have revised it for the *Journal*. Thus altered, it will be understood that what is meant is that at each half cycle the voltage wave will rise without any current flowing until the potential is high enough to bridge the arc gap resistance. The potential will then momentarily drop whilst the maximum current will flow. Towards the end of such half cycle, the current will stop almost suddenly when the potential falls too low to bridge the arc gap. At that moment when the current ceases to flow there is a slight rise of potential noticeable on the voltage curve. The result of the foregoing is to lower the power factor without any displacement of phase, it being understood that all this refers to arc phenomena proper with some reactance in circuit and not to furnace observations. This reservation is made quite clear in my paper. Replying to the last query of Mr. Crapper, the word "voltage" was omitted after the word "impedance" in the advance copies.

Mr. J. L. Thompson's comments on my suggested transformer requirements are much appreciated. Several of the points he raises I have dealt with in my answer to his colleague Mr. Ellis. I would quite agree with him that the current density in forced-cooled transformers should be taken higher than in naturally cooled ones, but only so long as the system of cooling did not solely consist of replacing hot oil with cooler oil. That is to say that forced cooling should always imply the forcing of cool oil against the windings. Mr. Thompson's remarks about my item (6) are a very good résumé of points often left unthought of in connection with transformers. Mr. Thompson says item (7) is a very contentious point. Certainly many have opposed this suggestion of mine; but hitherto it has only been objected to on the ground that the unavoidable reactance in the furnace circuits is either already sufficiently high, or else that any additional reactance to the ordinary circuit reactance is obtainable by juxtaposing reactance iron along such circuit. Mr. Thompson suggests another objection to a high transformer reactance. My first answer to all these points is that well-designed furnace circuits do not contain such elusive reactance factors as to leave in doubt whether sufficient reactance will be available to protect the installation. The second answer is that my adoption of about twice the voltage per phase found in all other plant cuts down the current flowing in my transformers to about one-half that obtaining elsewhere, and this overcomes Mr. Thompson's point. A high reactance in a transformer has the advantages of protecting the apparatus in case of a short-circuit across the low-tension circuits and in permitting ample spacing of coils for ventilation. If these most valuable advantages are obtainable at the same time as the high power factors which I show in my paper to be obtained with large Stobie furnaces, then surely objection should be raised against low-reactance transformers in future. Mr. Thompson is quite correct in suggesting that a delta high-tension arrangement should have been shown in Fig. 3. As one with a measure of experience in designing complete furnace equipments and with equal experience in running them, I cannot endorse the ideal transformer outlined by Mr. Thompson. I have dealt with the objections thereto in the discussion of his paper on furnace transformers.

Mr. D. G. Jones's remarks may be supplemented by giving the coal or coke consumption per ton of steel for manufacturing steel in efficient practice, viz.:—

Open Hearth	.. ..	7 cwt.
Electric	.. .. ..	10 ,,
Crucible	.. .. ..	60 ,,

I am glad to know Mr. Burnand agrees with my contention, as does Mr. G. M. Brown, that there can be no circulation of the bath in electric furnaces. It is possible, as Mr. Burnand further states, to force some circulation by special dispositions of magnetic fields in relation to current flow. This is seen in the Ferranti mercury meter which, by the way, Dr. Ferranti tells me resulted from his early experiments in Sir William Siemens's electric steel furnace. Dr. Ferranti originated many alternative electrical connections on that historic single arc furnace, and one of them consisted of winding round the crucible the cable carrying current to the top electrode. The other cable went direct to the bottom electrode. It was found that the bath circulated with a speed proportional to the current flowing. Such an arrangement is, of course, impracticable in a modern

electric steel furnace unless the latter is of exceptionally small capacity. I did not mention the use of external magnets in my paper as a suggested means of causing circulation of the bath, as would appear from Mr. Burnard's remarks; it was in connection with arc phenomena. Mr. Burnand's illustrations of the communal working of magnets are most interesting. Practice, however, does not agree with his deduction therefrom that separately wound transformers feeding separate electrodes under the conditions he names will pass current according to the potential difference between the electrodes. This certainly does not occur at all in circuits out of phase with each other by 90°, and I cannot see how it could happen even with separate transformers in step with each other. Let A in Fig. C

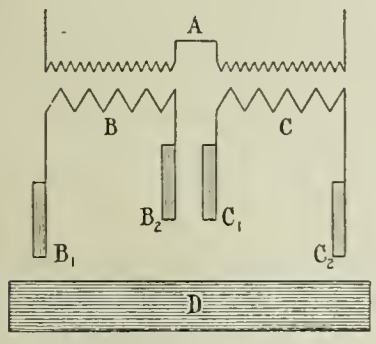


FIG. C.

herewith be a high-tension circuit through two transformers in series. Let B and C be separate low-tension circuits from those transformers, and B_1, B_2; C_1, C_2, the corresponding electrodes. Let D be the bath of steel. Assume a voltage of 100 between B_1 and B_2, and a similar voltage between C_1 and C_2. If B_1 and C_2 are brought down to half the distance of B_2 and C_1 from the bath, one would expect the voltages across the four arcs to be respectively 33; 67; 67; 33. Then if Mr. Burnand were correct two-thirds of the total current flowing through the bath should pass through B_2 and C_1, and one-third of the current through B_1 and C_2. This cannot occur as no current will pass through B_2 which does not pass also through B_1. Again, the relative voltage ratio of two arcs in series is roughly proportional to the distance of each electrode from the bath divided by the sum of their distances; therefore a higher potential on one arc is offset by the higher resistance of the arc gap. In the illustration (*b*) given by Mr. Burnand, the flow of magnetism is, as he suggests, in series and whatever lines of force pass through one pole pass through the other three. Its electrical equivalent only exists when connections permit a circulating current. If in Mr. Booth's Fig. 2, mentioned by Mr. Burnand, the hearth grids were not insulated from each other or if there were not a fairly high insulation between such grids and the metal bath, then a circulating current would readily flow and fulfil the conditions necessarily precedent to Mr. Burnand's assumption. Certain it is that instruments in the two circuits shown in my Fig. 2 conclusively demonstrate that there is no current in either low-tension phase which is not proper to that phase alone. It would be necessary to connect one side of one low-tension circuit to one side of the other low-tension circuit at any point between the transformer terminals and the electrode terminals to permit a circulating current to flow, as the potential difference behind the assumptive circulating current is insufficient to bridge the combined resistances of the four arc gaps, the potential being only 70·5 per cent of that necessary. Nor, in this case, can one expect even a proportion of circulating current equivalent to the proportion of voltage, as the arc gaps are adjusted for the higher phase-potentials. Circulating current in a two-phase furnace system lowers the power factor of the system. It also boosts up the voltage of one phase at the expense of the other, and thus throws the energy demand out of balance. For these reasons, and to gain the advantage of the buffer action of two arcs in series, I originated the entire separating of phases in large polyphase furnaces.

Mr. Moffett's remarks consisting, as they do, mainly of a résumé of the papers, do not raise more than one or two debatable points; but his belief in a circulation of the bath in an arc furnace would seem difficult to overcome.

In reply to Mr. Whittaker, so much depends on the ultimate energy consumption and furnace temperature that a useful arrangement for obtaining a flame spread in one size or type of furnace may quite easily be useless for another.

THE ALUMINIUM ELECTROLYTIC ARRESTER, WITH AN INTRODUCTION ON ELECTRICAL DISTURBANCES.

By A. G. Ramsey, B.Sc.Eng., Student.

(*Abstract of paper read before the* Students' Section, 15 *December*, 1915.)

Authorities of to-day agree that the main problems of protection against electrical surges and lightning disturbances have been solved, but there still exist many points, in the realms of both theory and practice, especially with regard to atmospheric phenomena, which have yet to be elucidated. In the following, therefore, only a few of the more or less predominant electrical disturbances are considered.

Briefly, surges may be classed into two main groups: (1) potential surges and (2) dynamic current surges. The former naturally involve a movement of a charge of electricity and are therefore followed by a current, but it is desirable to distinguish this surge current from the heavy dynamic currents which result, on a constant-potential system, from an accidental short-circuit. There is always a greater amount of energy in the dynamic current surge, which frequently causes great mechanical damage and excessive heating. The oscillating currents of abnormal potential surges rarely do harm in themselves, it is the abnormal value of the potential reached which so often causes the destruction of the dielectric.

The principal causes of abnormal potential surges may be sub-divided as follows: (*a*) Lightning, (*b*) accidental earthing, (*c*) resonance, (*d*) switching effects, reflected waves, concentration of potential, etc., (*e*) continuous induction.

Lightning.—The nature of the accumulation of static electricity in the atmosphere which causes lightning is still a matter of speculation. It seems probable that, as a result of very rapid condensation of moisture and the lack of uniformity of this condensation due to air currents, a non-uniform distribution of potential is produced between the raindrops in the clouds. When, at some point in space, the potential gradient exceeds the disruptive strength of air, an oscillatory discharge takes place between raindrops and gradually, in a number of successive discharges, traverses the cloud and equalizes the potential gradient within it.

From results obtained by E. Linke in numerous balloon ascents, the potential gradient appears to diminish the further we get away from the earth. Up to 1,500 metres it seems to vary daily and to depend upon atmospheric conditions, but about this height the gradient at any particular point tends to remain constant over long periods. Linke deduced the following formula:

$$dV/dh = 34 - 0{\cdot}009\,h,$$

where dV/dh is the potential gradient in volts per metre and h the height in metres above the ground, the formula being applicable to heights from 1,500 to 6,000 metres.

Assuming Linke's formula to be only a rough approximation which fits in with his experiments, the results show that at about 4 miles above earth the potential gradient is very small. During storms the distribution of potential is very erratic and it is impossible to fix any limits to the variations in potential; the gradient near the earth may be at least 10 times that during settled days.

Briefly, lightning may affect a transmission line in three ways: by static induction, by magnetic induction, or by direct stroke.

A charged cloud approaching a line induces, by static induction, a charge of opposite sign in the conductors; this charge rushes along the line and jumps to earth at any weak point. If, however, the insulation is everywhere strong enough to prevent discharge, or if the potential of the charge is not high enough to jump to earth, the charge will oscillate backwards and forwards along the line, dissipating its energy in ohmic losses and leakage. The field set up by a lightning discharge taking place parallel to a transmission line induces a charge by magnetic induction which may either jump to earth at a weak spot, or damp itself out as before.

A direct lightning stroke is rare and, if it strike a line at some distance from the station, it usually jumps to earth over the nearest insulator, often destroying both insulator and pole; also there will generally be a wave sent along the line which may, or may not, cause damage depending on local conditions. If the stroke occur near the station apparatus it is probable that no protection whatever will be obtained from any arrester. Even supposing that the arrester were a direct connection between line and earth there would generally be sufficient inductance and resistance in this earth connection to prevent a free discharge, and the result would be that the lightning would find other paths to earth as before. It may be said, generally, that lightning arresters are not required to discharge direct strokes.

Recent investigations seem to confirm that lightning disturbances may be either oscillatory or impulsive in character and that the possible frequency of discharge lies between half-a-million and a million cycles per second, the average duration of a direct stroke being about 2×10^{-6} second. Several discharges generally follow in succession, and what appears to the eye as a single discharge usually consists of three to seven, and in rare instances as many as a dozen.

Accidental earthing.—On overhead systems an arc to earth often destroys insulators and burns off portions

of the line, while on cable systems the arc quickly burns to the other conductors, thus causing a short-circuit; in addition, the rapid make and break of the arc sets up high-frequency disturbances. The usual location of these earths is at an insulator, transformer bushing, transformer or generator end-coil, or a cable joint. An earth occurring on one phase of an isolated neutral system when the voltage is a maximum (i.e. at the wave-peak potential) produces a maximum momentary rise of about 1·58 times the line or 2·7 times the star potential, the surge current in an overhead system being limited to the capacity current of the system as the return is over the electrostatic capacity of the other lines. The danger is reduced in the higher-voltage systems as the capacity to earth is greater, due to the increased height of the line, and the higher capacity also tends to keep the frequency of the disturbance below those frequencies which are liable to cause resonance.

An arc following the flash-over on an earthed neutral system constitutes a short-circuit and is thus less liable to become oscillatory; it is, however, far more destructive owing to the practically unlimited power behind it.

Resonance.—It is well known that a circuit containing capacity and self-induction has a natural periodicity of its own, and if the frequency of supply is made to coincide with the natural frequency very violent oscillations may be set up and exceedingly high potentials reached. The magnitude of these oscillations is limited by the "apparent" resistance (R) of the circuit, and if this be comparatively small the voltage across the capacity (K) or self-induction (L) may rise to approximately p L/R or $1/(p$ K R) times the supply pressure, where $p = 2\pi \times$ frequency.

The most general cases of resonance in practice occur with long unloaded cables connected to alternators and, in multiphase systems, certain combinations of transformers and cables may exist where, during switching or an open-circuiting of one connection, the self-induction of the transformers may be in series with the capacities of the feeders. Generally resonance of the fundamental and lower harmonics is very rare, but resonance of the higher harmonics is frequently observed, causing, however, no dangerous pressure-rises owing to the amplitudes of these higher harmonics being small.

Switching effects, reflected waves, etc.—Oscillograph records show that the danger of the disturbances produced by switching lies more in the high-frequency nature of the oscillations producing steep wave-fronts than in the extent of the over-voltage itself. Further, the disturbances on high-tension systems fed by transformers are of minimum effect when the circuits are closed on the low-tension sides of the transformers. This method of switching is naturally not always available, and the consequent closing of transmission-line circuits by high-tension switching often produces severe oscillations.

Consider the case of an unloaded line suddenly switched on to the high-tension side of a step-up transformer by closing the high-tension switch. The line capacity is shunted across the transformer and is charged through the line inductance and resistance. The severity of the disturbance will depend upon the point of the E.M.F. wave at which the switch is closed; if this be the peak point, full voltage is applied to the capacity and the maximum effect results. Assuming no losses, the potential across the capacity, i.e. the line, reaches twice normal voltage.

Again, if a transformer be switched on at the end of a line, high-tension switching is, of course, essential. The voltage at the end of the line may be 10 to 20 per cent above normal, and when suddenly applied an exchange of stored energy and a rush of magnetizing current take place, accompanied by a sudden rise of potential. Similarly, on breaking circuits the interchange between electrostatic and electromagnetic energy produces more or less dangerous oscillations.

The concentration of voltage on the end turns of transformers and generators at the instant of switching is the cause of many failures. The effect is often accentuated by arcing and vibration of switch contacts, thereby setting up high-frequency oscillations in the transformer and generator leads.

Another dangerous effect is the building up of potential at the far end of a transmission line on open circuit by the action of reflected waves. When the travelling waves reach the end of the line both the surge current and voltage (e) are reflected back, the reflected voltage wave having the same direction as the incident wave, thus increasing the amplitude momentarily to $2e$; the reflected current wave, however, is opposite in direction to the incident wave of current so that the amplitude is not increased.

Continuous induction.—A telephone line situated under a high-tension transmission line is continuously subjected to potential strains through both electromagnetic and electrostatic induction. If an earth occur on one phase of the transmission line the severe induced voltage in the telephone line may cause considerable damage.

On multi-phase unearthed-neutral systems an earth on the high-tension side of a transformer may induce very high potentials in low-tension windings unless the latter are earthed or connected to an electrostatic capacity of much greater value than that between the high-tension and low-tension windings.

Dynamic current surges.—Finally, the effects of short-circuits and current-surges generally result in excessive mechanical strains and overheating in the apparatus, and may cause interruptions of service. Such effects are often accompanied by abnormal potential disturbances, some well-known examples of which are given in the following.

When a heavy current arc "explodes," the sudden cessation of current produces an electromagnetic "kick" which raises the potential to an abnormal value. A short-circuit on one phase of a multi-phase generator or transformer causes a distortion and sudden increase of the flux threading the other phases, with the result that excessive potentials may be reached, especially on no load.

The Aluminium Electrolytic Arrester.

The function of a lightning arrester.—Lightning arresters are primarily designed to protect electrical systems from potential surges and lightning disturbances. When brought into operation they should afford a discharge

path to earth of lower resistance than that offered by the insulation of the line and apparatus connected to it; at the same time, they must be capable of holding back the line voltage and of suppressing or interrupting the arc following a discharge. The requirements are therefore somewhat conflicting.

There is no doubt that many engineers unreasonably expect lightning arresters to perform many functions for which they are not designed. An arrester is not a universal protection against every kind of interruption and disturbance. For instance, an arrester located at the station is not designed to protect insulators on the line from a direct lightning stroke; also there are certain low-potential surges and accidents due to faulty manufacture over which it will have no certain control.

Principles of operation.—The principles of operation of the aluminium electrolytic arrester are based on the properties of the aluminium cell, comprising two aluminium plates immersed in a suitable electrolyte. The most important characteristic of the cell is its "critical" voltage which is dependent upon the production of a film of aluminium hydroxide on the surface of the plates by subjecting them to chemical and electrochemical action. Below the "critical" voltage the film allows only an exceedingly small current to flow, but at a higher voltage the current is limited ultimately only by the internal resistance of the electrolyte. It has, therefore, a valve action analogous to that of a steam safety-valve. A countless number of these minute safety-valves are distributed over the plates and if the pressure rises above the critical voltage a discharge takes place uniformly over the whole surface of the film. On the voltage falling below the critical value the film will re-establish its property of resisting the passage of a current. Further, the thin hydroxide film between the aluminium and the electrolyte constitutes an electrostatic condenser which serves as an ideal path for high-frequency discharges.

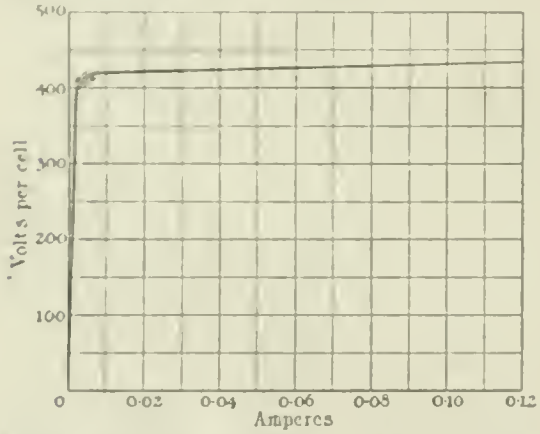


FIG. 1.—Volt-ampere characteristic of aluminium cell on direct current.

Electrolyte.—Exhaustive experiments have been carried out from time to time with various electrolytes, and some have been found objectionable because they attack the metal electrodes when the apparatus is not in use, while others are unsatisfactory because the structure and composition of the film are such that the critical voltage is lower than desired. If the cell be open-circuited for some length of time the insulating property of the film is impaired, probably due to the dissolving action of the electrolyte, and a further passage of current is required to restore its insulating properties.

The most satisfactory electrolyte is ammonium tetraborate, which is formed by dissolving boric acid in distilled water to form an 8 to 10 per cent solution, which is then mixed with an excess of ammonia solution containing about 25 per cent ammonium hydroxide, the resulting solution being evaporated over a water bath to dryness until all the ammonia smell has disappeared; the result is the most stable form of borate, $B_8O_{13}(NH_4)_2$. The best proportions for the electrolyte are

10 % ammonium tetraborate,
10 % concentrated glycerine, $C_3H_8O_3$,
80 % water,

which give approximately a saturated solution. An addition of glycerine still further reduces the action of the electrolyte in deteriorating the aluminium plates. The chemistry of the subject is not well understood, but the glycerine appears to react in some manner, as the solution becomes acid and must be neutralized again as before. It seems probable that this effect is due to oxidation on the part of glycerine to form an organic acid.

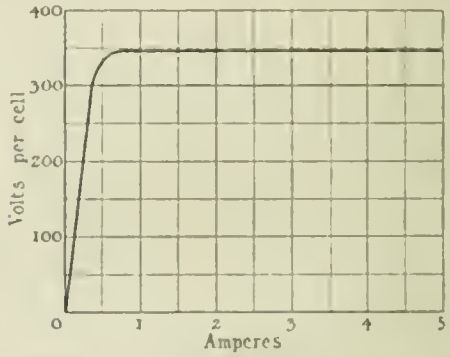


FIG. 2.—Volt-ampere characteristic of aluminium cell on alternating current.

Characteristics.—The operation of the aluminium cell will vary somewhat depending on whether alternating or direct current is used. With alternating current both half-waves are effective, one half on one plate and one half on the other, the cell acting as a fairly good condenser. There will be a capacity current, as well as a leakage current and the phase of this current will be nearly 90° ahead of the voltage, thus representing a low power factor. With direct current the discharge occurs only in one direction and a reversal of current dissolves part of the film and renders it inactive.

Figs. 1 and 3 show the volt-ampere characteristics of the cell on direct current with a permanent critical voltage of about 420, the data of Fig. 3 being taken from oscillograph records. The volt-ampere characteristic on alternating current is shown in Fig. 2, the permanent critical voltage being between 330 and 340 volts.

Fig. 4 gives characteristic curves of capacity, power

factor, resistance, etc., from which it can be seen that, when discharging, the current is limited only by the resistance of the electrolyte, which is very low. The thickness of the film is comparable with the wave-length of light, i.e. of the order of 40 to 80 millionths of a centimetre.

Due to the capacity of the cells, electrolytic arresters on alternating-current systems cannot be connected permanently to the line, as the charging current would heat up the electrolyte; hence, spark-gaps set at a slight increase over normal voltage are employed to insulate the arrester from the line. No spark-gaps are used on direct-current systems, as the normal leakage current is exceedingly small.

It must be pointed out that increases and decreases above and below line voltage will tend to thicken and diminish the film respectively, so it will be understood that there may be any number of temporary critical voltages up to the permanent critical voltage, which is the value at which the film cannot thicken further for

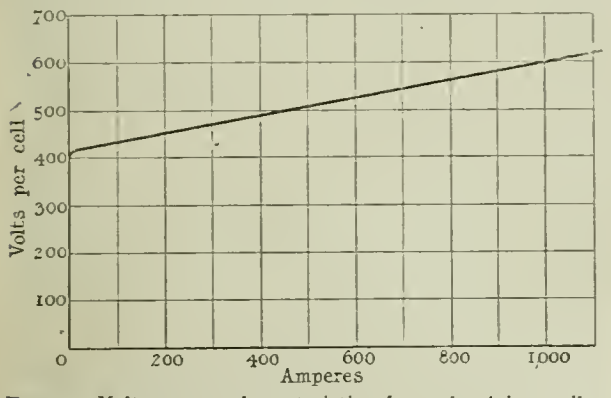


FIG. 3.—Volt-ampere characteristic of an aluminium cell on direct current, showing the rate of discharge above the critical film voltage.

any increase in voltage and at which free current discharge takes place. The number of cells, therefore, for a circuit of given voltage is so chosen that the normal alternating voltage per cell will be approximately 300 volts, i.e. slightly less than the permanent critical voltage. On direct-current circuits the value should be about 350 to 370 volts per cell.

The hydroxide film on the surface of the aluminium plates is made up of two parts, that next to the metal being hard and insoluble and acting as a frame for the more soluble part, which is probably composed of gases in a liquid form. If the cell be allowed to remain disconnected from the circuit there is a gradual dissolution of the soluble part of the film, and on reconnection to the circuit there will be a momentary rush of current to reform this dissolved part of the film. The magnitude of this current-rush increases as the intervals of disconnection are made longer, and in some cases it may become severe enough to operate the oil switches. When the period of disconnection, however, is not more than a day the film dissolution and current rush are negligible, so that it is only necessary to provide means whereby the cells may be connected to the line for a few seconds daily to ensure preservation of proper conditions. With direct-current systems the arrester is, of course, permanently connected to the line.

Construction of arresters.—Standard aluminium arresters are manufactured for all alternating-current systems above 1,000 volts and, at present, for direct-current circuits up to 2,400 volts. As most transmission lines are worked with three-phase alternating current the following description practically only deals with arresters for three-phase circuits, those for single and two-phase systems differing only in the number of units and connections. The construction varies somewhat depending on the normal voltage, on whether the system has isolated or earthed neutral, and on the location and arrangement of the station.

In the commercial arresters the plates referred to under the last section are cone-shaped trays placed one above the other with a vertical spacing distance of about 9/32 inch for voltages up to and including 27,000 volts, and 27/64 inch for circuits above this voltage, the trays

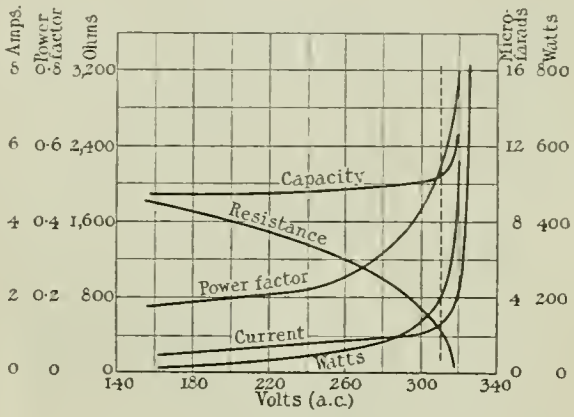


FIG. 4.—Characteristics of aluminium cell on alternating current.

being insulated from each other except for the electrolyte. The trays are sometimes insulated by fibre bushings, the whole structure being kept rigid by four equally spaced wooden rods passing through both the flanges of the trays and the bushings. Another method is to use four porcelain spacers equally distributed round the periphery of each tray, the whole stack of cells being clamped by wooden bolts passing through special guides to prevent lateral movement.

Each tray is filled with a measured quantity of electrolyte before the complete unit is immersed in a welded steel tank of oil; the electrolyte being of greater density than the oil, remains at the bottom of trays. A cylinder of insulating material is placed between the cone-stack and the tank to eliminate the risk of side-sparking and also serves to promote oil circulation. The oil improves the insulation between the trays, prevents evaporation of the electrolyte, and its heat-absorbing capacity permits the arrester to discharge continuously for long periods without overheating.

A stack of cones is provided for each phase, and for isolated neutral circuits and systems earthed through a resistance an additional stack is required for the earth leg (see below). Besides the tanks and trays the com-

plete arrester also comprises a supporting structure on which are mounted horn-gaps, transfer switch (if necessary), charging resistances and insulators.

Arresters for alternating-current circuits up to 7,000 volts and for direct-current systems have all trays mounted in one tank, but above this voltage each stack of trays is contained in a separate tank.

The horn-gaps (one for each phase) separating the arrester from the line on alternating-current systems fulfil a three-fold purpose:—(1) The cells are prevented from being permanently subjected to the normal voltage, thus eliminating the risk of overheating; (2) they act as isolating switches when repairing or inspecting, one horn of each gap being pivoted and equipped with operating mechanism for the purpose; and (3) they serve as connecting switches for charging and testing.

The controlling mechanism for operating the gaps generally consists of a rope and balance weights attached

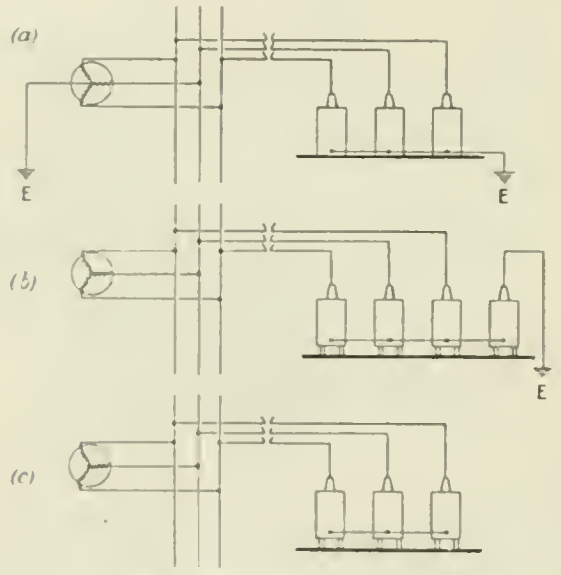


FIG. 5.—Diagrams of connections.

to three movable shafts which are held in position against a latch by heavy coiled springs. The shafts carry the movable sides of the horns which are provided with metallic projections for bridging the gaps for charging purposes. The latch block is adjustable so that the gap settings can be changed without disconnecting the arrester from the line and all gaps are operated simultaneously. The rope and balance weights are sometimes replaced by an operating lever and mechanism.

Charging resistances which limit the charging current to a moderate value, modify its wave form so that the action of charging has no effect on any resonant part of the system, increase the life of the trays and electrolyte, and ensure better operation of the arrester, are now recommended by most authorities. A modified type of gap is generally used with arresters having charging resistances, and consists of the introduction of an auxiliary horn mounted above and insulated from the main horns in such a manner as to intercept the arc if it rises on the main horns. The resistance is connected in series with the auxiliary gap, which is slightly smaller than the main gap, and the charging current is maintained nearly uniform.

The action of the modified gap is as follows:—Light discharges take the path of the auxiliary gap, and pass through the resistance to the arrester. If the discharge be heavy the resistance offers sufficient impedance to cause the spark to jump the main gap and, with the cells in normal condition, the arc is immediately extinguished without any flow of dynamic current. If the cells be in poor condition the dynamic current may follow the discharge across the main gap but the arc will rise and, on reaching the auxiliary horn, be suppressed through the resistance.

Fig. 5 shows the arrangement of arresters for earthed and isolated neutral three-phase systems. Briefly, for thoroughly earthed systems the bases of the three stacks of cones are connected to the tanks and earthed as shown in (*a*). For isolated neutral systems the arrangement is as depicted in (*b*), the tanks being insulated from the earth; the necessity for the earth leg is evident. With a system having the neutral earthed through a resistance of sufficient magnitude to prevent instantaneous operation of the circuit breakers when one phase becomes accidentally earthed, an arrester for an isolated neutral system should be used.

For three-phase networks consisting entirely of cables and operating with an isolated neutral the connections should be as shown in Fig. 5 (*c*), the bases of the three stacks of cells being connected to the tanks which are joined together by a multiplex connection and completely insulated from earth.

When an earth leg is installed, means must be provided for charging this leg to the same value as those connected directly to the lines. This is accomplished by means of a transfer switch capable of being rotated through 180°. In charging, the gaps are bridged twice, the transfer switch being reversed between the two applications.

The construction of the direct-current aluminium arrester is very similar to that used on one phase of a low-voltage alternating-current system except that the horn gap is not used, the arrester being permanently connected to the line. The direct-current arrester is ideal from the standpoint of protection, as dielectric spark lag is eliminated and, by its direct connection to the line, all surges of any potential and frequency are absorbed as soon as they reach its terminal.

Location of arresters.—It is obvious that arresters should be placed as near as possible to the apparatus to be protected and to the earth connection. They should not be exposed to excessive temperature, as overheating causes dissolution of the films; arresters will operate efficiently at temperatures up to 110° F., and for short periods at a slightly higher temperature.

The ideal conditions of installation, in the author's opinion, are to locate the tanks just inside the station in a suitable compartment, with the horn gaps, transfer switch, etc., outside the building, necessitating, of course, bushings through the wall for the connections; but much depends on local climatic conditions and transmission line terminal arrangements. Concrete founda-

tions for the tanks are desirable, and ample clearance between live parts and surrounding objects is essential.

Many lightning arrester troubles are traceable directly to poor earth connections, and the importance of this item cannot be too strongly emphasized. The usual method consists in earthing the arrester to a large metal plate in a bed of carbon at a depth of about 8 feet below the ground. A more satisfactory earth may be obtained by driving into the soil a number of $\frac{3}{4}$ inch galvanized iron pipes each having a galvanized point and brass connection cap at the other end, the total length being 8 to 10 feet with about 6 inches exposed. An arrangement of seven pipes in parallel distributed round the station, one at each corner of an imaginary regular hexagon and one at the centre, constitutes an excellent earth. A supplementary earth line should invariably be connected to the structural steelwork of the station, and to available water mains, etc.

In selecting protective gear for transmission lines, both generating and substation arresters must have the same rating, no allowance being made for line drop, as it is possible for the substation apparatus to be subjected to the generating-station voltage when the load is light or suddenly cut off.

Placing arresters in service and charging.—The aluminium trays, when shipped from the manufacturers, have the films partially formed and, after erection of the stacks of cones, it is necessary to test each cell to see that it has been filled and to complete the formation of the film. This latter is done by connecting 250 to 300 volts (alternating) to each cell successively, with a lamp resistance in series to limit the current to 2 amperes while testing. The lamps may first show bright, but as the remainder of the film forms they will gradually become dim. Absence of this brightness indicates that the film is already formed or the cell has not been filled with electrolyte. When direct current is used the operation must be repeated so that the voltage is applied to each cell in both directions.

It is advisable to set the horn-gaps to a medium value and watch the performance of the arrester for a few weeks, altering the setting until satisfactory conditions are obtained.

When connecting arresters to the line for the first time, which should be done as soon as possible after assembling to prevent film dissolution, only about half the normal potential should be applied and the gaps bridged for a few seconds. The condition of the cells can only be determined by observing the colour of the arc, the normal state being indicated by a bluish, crackling, static spark which tends to die out and does not rise much on the horns. A flaring reddish power arc, a feeble spark, or a rumbling sound in the tanks during charging indicates a bad state of the cells. It must be pointed out that the external appearance of the trays gives no guide to their condition.

The daily charging period, especially with charging resistances present, need only be for about 10 seconds, but all charging should be done when the line voltage is a maximum, as the working critical voltage of the arrester is the voltage at which it was charged.

Auxiliaries.—Choke coils, when used in conjunction with arresters, should be so arranged as not to prevent surges originating in the transformers from passing to the arresters.

A charging-current indicator, consisting of an ammeter mounted on a plug which fits into automatically closing jacks on the tanks should be provided so that conditions of charging may be accurately known.

A discharge recorder should be installed so that a continuous record of arrester discharges is available. This recorder consists essentially of four spark-gaps so arranged that discharges between lines, or between lines and earth, pass through them, the continuous record being obtained by means of punctures in a moving roll of paper rotated by clockwork. The size of the punctures indicates roughly the conditions of the arrester.

Conclusion.—These arresters are primarily designed to protect station apparatus and are of little value in protecting transmission lines themselves, but to a certain extent protection is afforded to line insulators in the case of travelling waves and such-like transients.

The status of the aluminium arrester is that of a protective device founded on the sound principle of the safety valve. It is no different from other standard apparatus in that there are definite limits of maximum current discharge rate and of energy absorption beyond which damage to the arrester will result. That these limits are far above the usual demands of practice is demonstrated by the fact the arresters are capable of being discharged continuously for half an hour. It is not impossible to pass these limits, but it must be remembered that there is great flexibility to meet special conditions—film surface area, gap settings, internal and external resistance are all adjustable to meet any unforeseen demands.

ELECTRIC RAILWAY TRACTION.

By A. G. Everett, Student.

(*Paper read before the* Students' Section, 28 *March*, 1917.)

The last six or seven years have seen a rapid advance in the electrification of railways, more so in America and on the Continent of Europe than in Great Britain and other parts of the world. In America new lines have been laid down and existing ones electrified for both passenger and freight working. In England, however, electrification has been practically confined to Tube railways. The great difference between England and America is that England is covered with a network of railways and new lines are rare, while in America new towns are continually springing up, so that electric railways can be laid down from the start. Also, in America and on the Continent of Europe a great amount of water power is available for use in power stations, whereas in England the generators must be driven by steam power and the cost of generation is much greater than with water power.

The three systems of electrification in use to-day are:—

(1) Direct current at 600, 1,200, 1,500, and 2,000 volts.
(2) Single phase current at 3,000, 6,000, 11,000, and 22,000 volts.
(3) Three phase current at 3,000 volts.

In America, direct current is used with a third rail on about 50 or 60 railways, the voltage commonly adopted being 600, although 1,200 volts is used in several cases. In Europe there are from 30 to 40 railways using direct current third rail systems. Out of the above railways, seven are on the three-wire system, the chief case in England being the City & South London Railway.

The direct current used in most cases is generated as three phase current at 60, 35, or 25 cycles at high voltage, transformed to a lower voltage, and converted to direct current by rotary converters. Direct current traction is also employed with overhead conductors, but the voltage is then usually 2,000.

The three phase system was first used in 1895 on the Lugano Tramway, and its first application to railways was on the Burgdorf-Thun Railway, opened for traffic in 1899, the line pressure being 750 volts. In subsequent installations the line pressure has been raised to 3,000 volts, the two notable examples of this being the Valtellina line and the line through the Simplon Tunnel.

Single phase traction was not possible for some time, owing to the difficulty of obtaining a satisfactory motor. It was known that a direct current series motor would run with single phase current as well as with direct current, but the two principal objections to it were (1) the heavy sparking at the commutator, (2) the very low power factor and large wattless current due to the windings, large air-gap and magnetic leakage.

The first actual commercial example of single-phase traction was operated by compensated repulsion motors, and was on the Stubaithal line near Innsbruck. Single phase traction is used on the London, Brighton & South Coast Railway and on the Midland Railway in England, and on many American lines.

Since the commencement of electric traction the line pressure has risen from 100 volts to 2,000 volts (d.c.), and also to 50,000 volts single-phase. Electric locomotives have increased their hauling capacity from 50-100 tons to 2,000-3,000 tons with freight trains, and to 900 tons with passenger trains. It has been found that it will pay to electrify a railroad if more than 15,000 tons pass in one direction daily.

A.C. and D.C. Systems.

In either system a third rail may be used and the running rails employed as the return, or an overhead wire substituted for the third rail. There is also a system in which the supply is obtained from a third rail and returns by another insulated rail.

For railway work, the third rail seems to be the favourite system, the great difficulty, however, being the protection of the live rail. The most satisfactory system is that in use on the New York Central Railroad. Attempts have been made in America, and also in England, to standardize the third-rail system so as to permit of through running, and although no agreement has yet been come to, it is probable the above system will be adopted. In railways where many cross-overs occur, such as outside termini, great complication arises owing to the third rail, and in some railways so great has this complication become that an overhead wire has been used in places. This point shows the disadvantage of third rail systems.

When the maximum drop in voltage along the earthed return must not exceed 7 volts, a fourth insulated rail becomes necessary.

For small railways, such as the Tubes, a third rail may be adopted, but for main-line systems the overhead conductor should be used. The third rail is also a source of danger in a goods yard or where goods traffic is being handled.

Overhead System.

The first overhead conductor for main-line work was that originally adopted by the Baltimore & Ohio Railroad, now superseded by a third rail. The conductors were two Z shaped bars weighing 30 lb. per

foot. Wires and not iron bars are now used for the overhead conductor. Copper is used in most cases, but steel wire is used on the New York, New Haven & Hartford Railroad. Aluminium wire has been largely used lately, owing to its extreme lightness. For high-tension work porcelain insulators must be employed, and the insulation must be of such a quality as to keep its insulating properties for any length of time without showing the least sign of deterioration. Very high mechanical strength is also required in suspension insulators for traction work. The tensile stress of good porcelain is 10 tons per square inch. Insulators are tested for some time, at least 30 minutes, at from 4 to 10 times their working pressure, with a capacity of at least 20 k.v.a. and preferably 50 k.v.a. in the testing transformer.

For overhead work the following three conditions are necessary :—

(1) Practical impossibility of mechanical breakdown.
(2) Provision must be made as far as possible for avoiding electrical breakdowns, and construction must be such as to enable prompt repairs to be executed in case of failure of any part.
(3) The system must be sectioned, so that a failure will only affect one section, leaving the rest of the system in proper working order.

The forms of construction so far adapted to fulfil the above requirements can be subdivided into two parts : (*a*) single catenary construction ; (*b*) double catenary construction.

Double catenary construction has been adopted on a very large scale in America in connection with the New York, New Haven & Hartford Railroad in and around New York. The above construction is also in use on the London, Brighton & South Coast Railway.

Single catenary construction has been adopted on the railways in Sweden and Norway. On the single-phase railway between Seebach and Wettingen the overhead conductors are so sectionalized that they are interlocked with the signals, and until a rail is made clear by the signal there is no current in it.

Overhead construction is generally used with alternating current and the third rail with direct current. With the three-phase overhead system, three overhead conductors could be used instead of the track being employed as the third conductor. An attempt has been made to use the three wires vertically above one another. This was carried out on the experimental line in Germany and, so far as I have been able to ascertain, has found no commercial use. It is my opinion that for main-line electrification the double-catenary construction will be used, and for suburban systems the third rail. For lines having crossings, and for goods yards, the overhead system is essential, but here a disadvantage comes in owing to the difficulty of loading wagons by means of cranes.

The current is collected from the conductor by a metal shoe on the third rail system, and by a bow collector for the overhead system. The collector strip on the bow is usually of aluminium alloy and thus takes the wear rather than the conductor. The average life of a collector is 20,000 miles.

Advantages of Electric Traction.

Electric motive power means ample draw-bar pull and high speed. At present, most freight trains have electric locomotives to haul them, but tests have been made with the multiple-unit system on 2,000- to 3,000-ton trains, instead of with locomotives, and in the future this system will undoubtedly take the place of locomotives, for the tractive effort is more evenly distributed over the train.

In the case of the Manhattan Railroad of New York, formerly from the point of earnings one of the largest steam railroads in the country, steam trains could haul at the most only 4- or 5-car trains at 11 to 12 miles per hour. The railroad was elevated, and the elevated structure could not be rebuilt or strengthened. Electric power was introduced in 1902 and completed in 1903. There was an increase of 33 per cent in the carrying capacity of the road. The electric trains now have 6- or 7-car trains, running at 13·5 to 15 miles per hour, also the operating expenses dropped 10 per cent and the traffic lost by competition was regained. Most other railroads adopting electrification have had similar experience to the above railway.

On the New York Subway of the Interborough Rapid Transit Company, on a four-track road 66 trains pass a given point in an hour in each direction. Electro-pneumatic brakes can stop a train running at 40 miles per hour in a distance of 365 ft. Each 10-car train is equipped with motors equal to 3,200 h.p., or more than twice the horse-power used on steam-hauled trains. Steam railroads cannot even approach these results.

The simplicity of electric traction is evident, for we have the eccentric strap, rocker arm, valve gear, reciprocating valves, pistons, piston rods, cranks and unbalanced driving wheels in one case and the simple rotating motor in the other case Fewer parts reduce wear, tear, and maintenance.

Electric traction is safer than steam traction in many ways, and there is no doubt that safety appliances will be brought in the future to such a state of perfection that it will be practically impossible for accidents to happen, no matter how frequent the service. With electric motors we do not get track pounding, as we do with steam locomotives due to the reciprocating parts of the engine. Control circuits prevent accidents, also automatic devices are already installed which shut off the power instantly if the driver removes his hand from the control handle. Tunnels are made safer with electric power ; the walls are whitewashed, the rails are not greasy and slippery from the condensed steam, smoke and gases do not suffocate, the risk of fire from sparks is decreased, and there is no smoke or steam to obscure the signals and track. Electric meters are placed in the driving cab and indicate the horse-power supplied to the motors, and a glance at the meter shows how the train is accelerating.

The reliability of electric traction results from its simplicity. Reliability of service has been radically increased by electric traction, particularly on trunk lines and terminal service.

The adoption of electric traction has generally increased the gross earnings, and in America the suburban

lines of most railways are worked by electric trains, securing a more punctual and frequent service than with steam trains. The only railways which use electric power extensively in this country for suburban services are the London, Brighton & South Coast Railway, employing the 6,600-volt single-phase overhead system, and the London & South-Western Railway with a 600-volt third-rail system.

The railway which handles the heaviest freight and passenger train service most advantageously will find the preference given to it. Electric roads up to the present certainly have acquired and retained traffic, and as time goes on further developments will take place. Goods traffic is handled more expeditiously by electric locomotives than by steam; and with the heaviest traffic, and on grades, this traffic is neither bunched nor delayed, because with ample central-station capacity it is not necessary to reduce the loads or the speed. Some railways have already equipped freight trains with electric motors, which enable larger loads to be handled.

The present method of operation with steam traction calls for a load which the locomotive can just drag up the ruling grade. The locomotive runs at 6 to 12 miles per hour, delays all overtaking and opposing traffic, and during 40 per cent of the time is held up at the sidings to avoid other traffic. The results are not only a waste of fuel, high maintenance per ton-mile, waste of time and labour, but also a loss of time to other trains, inefficient use of track, procrastination in freight delivery, extra investments, car and locomotive shortage. Moreover, a heavy tonnage per train appears on the office accounts. Another advantage, and probably the chief, is the rapid acceleration of electric trains, which allows the maximum speed required for a given schedule to be reduced, with a consequent reduction in the amount of energy which has to be dissipated by the brakes, and therefore of the energy required to run the train. On the Metropolitan District Railway a speed of 3 miles per hour was attained in 10 seconds, while in the experiments carried out by the General Electric Company a speed of 30 miles per hour was reached in the same time.

Electric trains on the multiple-unit system have the great advantage of distributing the weight more evenly over the track, and also of permitting a smaller weight on each driving axle than with steam. For the same weight on the driving wheels an electric motor can exert a much greater tractive effort.

The cost of operating electric trains is also reduced, for only one driver is required.

An example of the increase in traffic, receipts, etc., by electrification is shown by the Mersey Railway.

Year	Expenditure	Receipts	Train miles	Passengers
1903 ..	£33,500	£38,327	154,272	3,720,000
1904 ..	£38,700	£52,103	403,030	5,720,000

On the North Eastern Railway as a result of electrification there was an increase of 17·1 per cent in the gross earnings, and an increase of 25 per cent in the number of passengers carried.

Electric locomotives are now used with considerable success on many railways, the first to adopt them being the City & South London Railway, and they are still used on this line, the armatures being wound directly on the axle. Instead of being wound directly on the axle the armature can be wound on a spider, which is spring-hung from the axle and is driven by some form of rigid coupling.

In the case of the locomotive constructed for the New York Central Railroad the designers claim to have secured the best mechanical features of the high-speed steam engine, combined with the enormous power and simplicity in control of the electric drive. The locomotive has four driving axles, on each of which is mounted the armature of a gearless motor, having a normal rating of 550 h.p. This locomotive was more powerful than any steam locomotive in existence at the time.

Geared locomotives.—In some geared locomotives the motors are placed higher up in the locomotive than before, and also the centre of gravity is raised, an important point in powerful and fast locomotives. Locomotives are more economical to maintain than motor coaches, for many reasons, such as facilities for constant supervision of motors and auxiliary apparatus. Gearless locomotives need less looking after than geared ones.

The advantages of electric over steam locomotives are:—

(1) In low-speed hauling.
(2) In shunting, savings for supplies, lower unit fixed charges and repairs.
(3) High speed, supplies, wages, fixed charges and repairs. The small increase in power (18 per cent) for greater speed is in marked contrast to the 105 per cent in coal consumption for steam traction.
(4) Cessation of corrosive action on metallic structures.
(5) Electric locomotives can run as efficiently backwards as forwards, which is not the case in steam locomotives.

Enough has been said to show what immense advantages, principally of an economical nature, would be gained by doing away with steam locomotives, at any rate in urban areas. I think that, as far as suburban areas are concerned, all trains, main line as well as suburban, must eventually be operated electrically, the former being operated by electric locomotives, and the latter by motor-coach trains.

Comparison of D.C. and A.C. Systems.

In all cases it is found that the weight of an a.c. motor is greater for a given output than that of a d.c. motor, and also the weight of equipment necessary for an a.c. motor is greater. With single-phase the total weight per rated horse power of motor equipment is 82·67 lb., compared with 54·83 lb. for a d.c. motor. Where there is so large a difference already between different d.c. machinery as manufactured by different makers, we cannot say that all single phase equipment must greatly exceed the equivalent d.c. plant. What it really amounts to is that d.c. and single-phase motors considered by themselves differ so little in weight that

any difference which may exist is unimportant from the user's point of view. Single-phase equipment necessitates transformers, but on the other hand, owing to the practical absence of resistances and simplicity of speed regulation, the weight of speed-controlling and reversing apparatus is much smaller than with d.c. equipment.

The direct-current motor as at present designed may eventually work at pressures up to 4,000 volts, but in future the voltage will be at the lowest 20,000, by reason of the transmission economy; and as high voltages only can be used for main-line electrification it seems to me that d.c. traction will only be used for small railways such as Tube railways. For main-line work the single-phase system seems to be the most suitable, although the cost and size of the motors for the same output is greater than for d.c. motors; but what is lost in this respect can be made up for by using high line pressures. One thing, however, we must not forget, namely, the higher the line pressure, the greater the difficulty of insulation becomes. Safety is also another thing that must be considered.

In 1913, out of 23 of the principal railways in the world, 15 were using single-phase current at 15 and 25 frequency and at from 3,000 to 15,000 volts, the present tendency being to employ anything from 11,000 to 22,000 volts; and six railways were using direct current at a pressure of 600 volts, the tendency, however, now being to adopt 1,200 volts.

Under ordinary conditions in electrification, economy demands that the electrical energy be generated and transmitted in the form of alternating current. For any pressure up to 10,000 volts there is no reason why the current should not be generated at that pressure, thus doing away with the cost of transformers, while for higher voltages the current should be generated at a lower pressure and step-up transformers used. High pressures on the working conductors are absolutely necessary, and pressures below 6,000 volts cannot be used successfully on long-distance work. The London, Brighton & South Coast Railway use 6,600 volts, the New York, New Haven & Hartford Railroad 11,000 volts, the Seebach-Wettingen line in Switzerland 15,000 volts, and the Swedish State Railways at Stockholm 20,000 volts.

In the above comparison I have left out all mention of three-phase traction. The obvious disadvantage is that two overhead conductors are necessary, which must be fairly near together to allow the current to be collected. This condition prevents a high voltage being used, and it is found that 3,000 volts is the limit between the conductors. The speed control of three-phase motors can be effected by varying the resistance in the rotor circuit, which is wasteful. Another method which, although increasing the number of windings, has given good results, is that where the number of poles is varied. Messrs. Brown, Boveri & Company have carried this out successfully in the case of the Simplon locomotives, the motors of which have only two speeds, corresponding to 30 and 60 miles per hour. On main lines only two combinations of poles are necessary, while on a service having more frequent stops more combinations would be required.

In considering three-phase traction we must note:—

(1) There is no possibility of making up lost time outside the maximum speed fixed by synchronism.
(2) Two overhead conductors are necessary.
(3) The three-phase motor does not lend itself to high starting acceleration.

The advantage of three-phase traction over single-phase is that the motors weigh about 63 lb. per horse-power, compared with 82 lb. in single-phase motors. Three-phase traction operating at 3,000 volts, with two overhead contacts and only two speeds, cannot, however, compare with the single contact, high pressure, and complete range of speeds obtained with single-phase traction.

Although the single-phase system has the great advantage of being able to use up to 20,000 volts on the conductor, results have been obtained with the 3,000-volt d.c. overhead system which are worth noting. The system to be described is the only system in the world in which electrification has been carried out over so long a distance.

The Chicago, Milwaukee & St. Paul Railroad electrified their mountain division first, and it was open for operation nearly a year ago. The entire system is now electrified, aggregating some 440 miles in length. In crossing the mountain ranges there are grades of 1 per cent and above, numerous tunnels and difficult curves. Up to the present time the results of the electrification have been excellent. It has been found, for example, that on a 20-mile, 1 in 50 grade, the electric locomotive can reduce the running time of passenger trains from 65 minutes to 40 minutes. In freight service where steam locomotives required 10 to 12 hours to travel 115 miles, electric locomotives take from 7 to 8 hours. Trains of 4,000 tons have been hauled by a single locomotive on grades less than 1 per cent.

Regeneration on the descending grade reduces the cost of operation and furnishes a solution of the difficult braking problem. With regenerative braking, the motors become generators, which absorb the energy of the descending train and convert it into electricity, thus restricting the train to a safe speed down the grade, and at the same time returning power to the line. This scheme includes the generation of current from several water-power plants, transmission at 100,000 volts 60 cycles, conversion in substations to 3,000 volts (d.c.), and distribution over catenary overhead construction to locomotives.

There are 42 main-line locomotives, each weighing 282 tons and capable of a starting force of 136,000 lb. They are the first to be used for railroad service with direct-current motors operating at a potential as high as 3,000 volts, and the first to use d.c. regeneration. The passenger locomotives can haul an 800-ton train at 60 miles per hour, and the freight locomotives a 2,500-ton train at 16 miles per hour. Each locomotive is equipped with eight 500-volt motors, insulated for 3,000 volts to earth. Fourteen substations are equipped for converting the 100,000-volt alternating current to 3,000-volt direct current. They are distributed along the route at average intervals of 32 miles. Each

station contains transformers, motor-generator sets, switchboards, and the necessary controlling and switching equipment.

Automatic Control.

During the last few years the automatic control of trains has increased considerably, and on many railways signalmen are only employed at terminal stations where points have to be changed, for on the rest of the line the signalling is carried out by the trains themselves. The signal at the commencement of the section is at danger as long as the train is on that section, and in all cases an overlay of 200 or 300 yards is allowed, so that the line is not clear until the train has travelled 200 yards of the next section. As already stated, arrangements have been made so that the train entering one section of a line automatically cuts off the current in the section behind, thus preventing any possible chance of one train running into another.

The "dead-man's" handle, in use on all electric railways, consists of a button on the controller handle, so arranged that the current is cut off if the driver removes his hand, and in some cases the car brake is applied.

The doors of the coaches should be so arranged that they can only be opened when the train is standing still, and locked when the train is in motion. If the train is forced to come to a standstill anywhere but in a station, a device should be installed so that the driver can still keep the doors locked.

Everything possible must be done to prevent accidents and loss of life. By using the overhead construction, less danger results from electrocution than with the third rail.

Power Stations.

Where power stations are dependent on coal and not on water supply they should be situated in such a position that a good supply of coal is readily obtainable. They should also be so situated that the sectionalizing of the conductors can be carried out with the least possible amount of cable. For d.c. work the current is generated as high-pressure alternating current and transmitted to substations, being there transformed down and converted to direct current. Substations increase the capital cost of electrification, and this is one of the reasons why a.c. traction has come to the front in recent years. The rotary converter in the substation, although it may not need constant watching, needs more supervision, thus involving many times the cost in wages, lubricants, cleaning, repairs, etc., than does a static transformer. Besides the substation we have three losses of efficiency, one in the static transformer, one in the motor side and one in the generator side of the converter, compared with the single loss in the static transformer used for alternating current. With a.c. traction very much higher pressure can be used than with d.c. motors, and thus each substation can feed a longer stretch of line.

Power having used for supplying electric railways when electrification is carried out on a large scale will certainly not have a smaller unit than 10,000 k.v.a., and these will be driven by turbines. An output of, say, 50,000,000 units per annum, allowing 2½ lb. of coal per unit, would require something like 56,000 tons of coal per year. It will therefore be obvious that although theoretically the power station should be as close to the centre of gravity of the electrical system as possible, by far the most important items to be considered, outweighing all the others in financial value, are plentiful supplies of coal and condensing water. It is essential in designing a power station that, while the greatest possible simplicity is observed in its layout and in the plant installed, due regard must be taken to ensure ease and economy in operation and maintenance. Future extensions must be borne in mind, and in selecting automatic switches, etc., care must be taken that their efficiency is high and cost of maintenance low.

For electric traction of the future to be successful from all standpoints, it is essential that very large generating stations should be built, and so built as to allow of further extensions, and that the stations should be within easy access of water and a plentiful supply of good coal. Single-phase current should be generated at a high voltage, say 22,000, and fed to the line at this pressure, as has already been done on the Swedish State Railways. By doing this the cost of substations is done away with, and a higher efficiency is obtained. The above plan could be carried out in America and where water power is available, but in Europe, particularly in England, it will be difficult to do so, and this is one of the things that will hinder electrification in this country.

In my opinion, the single-phase high-tension overhead system will be used in the future for all traction other than Tube railways. The future development of the single-phase motor will increase the popularity of the system, and the only thing that will retard electrification in this country will be lack of capital. The capital cost of electrification is heavy, especially for existing steam lines, but once the system has been installed, the facilities it offers to travellers will amply repay the railway company.

Of course the system adopted by a railway depends on the conditions, but in future some standard system should be adopted so that the trains may run on all lines. The single-phase motor can run on direct current as well as on alternating current, and thus these two systems could be connected up. Although the single-phase system has rapidly come to the front, the direct-current system is in no danger of being done away with, as the example of the Chicago, Milwaukee & St. Paul Railroad clearly shows, for excellent results have been obtained with 3,000-volt direct current. Only time will show which system will be used in the future, for as yet electric traction is still in its infancy and, although it has shown that steam traction will be superseded, one cannot say on what lines electrification will be carried out.

WORKS STANDARDIZATION OF PYROMETERS.

By R. Gates, Student.

(*Paper read before the* Students' Section, 28 *February*, 1918.)

This paper describes methods of testing some of the various types of pyrometers in industrial use, the methods of test to be such as could be reasonably carried out in the average works and require no special apparatus.

Pyrometers naturally fall into two distinct classes, requiring quite different treatment. The first to be dealt with is the contact type, i.e. where some part of the apparatus is at the temperature being measured. The second is the radiation or optical type in which no part reaches a high temperature, unless it be a lamp used as a standard for comparison.

Contact Type.

There are several sources of error which cause needless friction between pyrometer makers and the users, and which can be easily avoided by the most ordinary care in testing. Of these, one of the chief is the variation in reading obtained by a pyrometer or thermometer due to the depth of immersion in the hot material of which it is desired to measure the temperature.

Testing in position.—Instruments whose temperature scale is sufficiently low to permit it, are often tested against mercury thermometers. Such instruments are not infrequently tested in position, as their removal would necessitate shutting down the plant when they are in use in steam pipes or in the distillation of tar or oils. There are often in the pipe or vessel several pockets for the insertion of a pyrometer stem or couple if of the thermo-electric type, or bulb if of the resistance type, or a thermometer. The pyrometer stem is inserted into one pocket and probably reaches to the bottom, whilst the thermometer is lowered into another just far enough to allow a reading to be taken, which may mean that it has an immersion several inches less than the pyrometer stem. The result is that the pyrometer reads considerably higher than the mercury thermometer.

Sometimes the pocket in which the thermometer is inserted is of most unnecessary thickness, being in one case, I remember, about $1\frac{1}{2}$ in. diameter outside and $\frac{3}{8}$ in. inside. The pocket was further provided with a large nut at the top and was screwed into a mass of metal forming the top of a valve. The pocket was partly filled with oil. A mercury thermometer was placed in this pocket with just sufficient immersion to allow readings to be taken; and there was a similar pocket in a similar valve a foot or so further along the pipe. A thermo-electric pyrometer was used in this and gave readings about 30 degrees C. higher than the thermometer, the pyrometer stem touching the bottom of the pocket. At the suggestion of the pyrometer suppliers a longer thermometer was obtained to reach the bottom of the pocket, i.e. an immersion 3 inches greater than with the thermometer previously used. The long thermometer showed a reading only 3 or 4 degrees lower than the pyrometer.

A fairly steep temperature gradient is established along a pocket of the above dimensions, due to conduction, the heat being dissipated at the top where the pocket is exposed to the air. Moreover, a further source of error may arise due to the formation of strata of different temperatures or to stagnation of the fluid around one pocket and not the other, causing a very considerable difference in temperature of the two pockets.

An article entitled "Some Sources of Error in Thermometry," setting out these matters at more length, appeared in the *Electrical Review* of 29th December, 1916.

Dismantled for testing.—For low temperatures, where the instrument can be removed at will, a test against a mercury thermometer is the simplest method available. In this case the pyrometer bulb or stem and the thermometer should be close together in the fluid in which they are being heated. The same immersion should be given to each and care should be taken that it is sufficient for a correct reading with both instruments. A 3 in. immersion should be used for a gas-filled thermometer and is enough for many thermo-couple instruments. The fluid should be well stirred, and this is particularly necessary when using a heavy oil. Tests up to about 300° C. can readily be made by this method.

Testing at fixed points.—When making tests at the boiling point of water it is quite usual to boil a bucket of water and insert the pyrometer bulb or stem in the water. In many cases such a test is quite suitable, and it is seldom that an error of as much as 1 per cent will occur. For closer work, the part of the instrument to be heated should be immersed in the steam above the boiling water.

The boiling point of sulphur, 444·4° C., is another point which is extremely useful, and is very satisfactorily fixed. Pyrometers of the resistance type are frequently calibrated and tested in this way, the bulb being immersed in the sulphur vapour. This test hardly comes within the scope of this paper as it necessitates apparatus not readily obtainable in most works.

A tin, with good joints and two holes through the lid, one for the bulb and the other for the escape of the sulphur vapour, is not a success although it looks so simple. The sulphur vapour burns on escaping, with very unpleasant results; but any person hardy enough to go through with such a test will, provided a sufficient immersion of the bulb be secured, obtain quite good results.

Lead and salt points.—The tests most used are the freeze points of various metals and salts. Two points, those of lead at 327° C. and common salt at 800° C., suffice to test a very large proportion of the pyrometers of the contact type in commercial use. In fact, with the exception of instruments such as are required for superheated steam, etc., which are tested against mercury thermometers in oil, it is a very rare occurrence that one (or both) of these two points does not suffice. I have seen many hundreds of instruments tested on these two points, and such tests are quite simple and satisfactory. A crucible or iron pot of lead or salt, as the case may be, melted in a forge or other available furnace, if of sufficient size, satisfies the requirements as to apparatus. When a pyrometer user tests his instrument at one of these points and finds that it reads low (the usual complaint) it is frequently due to an insufficient immersion of the stem. No definite figure can be stated, as it varies with each type of stem. The depth required in lead is considerably less than that required in salt. The low reading is due to the conduction of heat along the stem, causing the tip of the thermo-couple to be at a lower temperature than that at which the change of state occurs.

If the stem be of the type—much favoured now among makers of base-metal pyrometers—with a Eureka or constantan wire passing down the centre of, and insulated from, a steel tube and welded at the tip, a depth of immersion in lead equal to two diameters appears to be just enough.

In a test which I made, using a stem of the type mentioned, with an external diameter of $\frac{5}{8}$ inch, the electromotive force at the freeze point of lead was 17·3 millivolts at 1 inch and was not raised by an increase of immersion to $7\frac{3}{4}$ inches. In salt, using an exactly similar stem, a greater immersion was found to be necessary. With 1 in immersion, 40·3 millivolts were generated at the change of state; with 2 inches this had increased to 45·2, at $2\frac{3}{4}$ inches to 45·6, and at $3\frac{3}{4}$ inches to 45·6 millivolts, i.e. in salt a depth of immersion equal to four times the diameter gives satisfactory results with this type of stem. It is very inadvisable, however, to work to the limit. If such a stem were immersed to a depth of four times its diameter when the salt were molten, it would be found that the very considerable shrinkage of the salt on freeze had much decreased this depth. For the reasons stated above, it is obvious that the less the diameter of the sheath the more simple the test is. Any protecting sheaths generally used with the instrument should, if possible, be removed for testing.

Where it is advisable to use a sheath for testing, to avoid contamination it should have an internal diameter only a little greater than is necessary to take the stem. Where such a sheath is used it is the outside diameter of the sheath that controls the immersion required, and not the stem inside.

A test made with a stem of about $\frac{3}{8}$ in. diameter externally, and a pocket of $\frac{3}{4}$ in. steam barrel, did not show any definite pause at the lead point, although the pocket was immersed $7\frac{1}{2}$ inches in the lead. A very apparent reduction in the gradient of the cooling curve was shown, but it was spread over about 4 degrees C. This, taking the average figure, would be sufficiently accurate for most industrial work.

Exactly the same remarks apply to salt points when the stems are in pockets. Sufficient accuracy is assured for industrial work with a length of the stem equal to six or eight times its diameter to be at a uniform temperature. For a salt point this judgment of uniform temperature may be made by eye.

Copper point.—The copper point is another extremely useful one for industrial work. It presents, however, difficulties which make it unsatisfactory for use in untechnical hands. The atmosphere in which the copper is melted and cools affects this point to a very considerable degree. The fixed point is 1,083° C. in a reducing atmosphere. In an oxidizing atmosphere the melting and freeze point may be lowered to 1,005°, i.e. a difference of 18 degrees C., but the probability is that the point obtained under conditions such as suggested for previous tests is somewhere between the two. The figure 1,083° C. is often stated for the melting point of graphite-covered copper, but however carefully we may cover the copper with graphite during the test, we may find on examining it afterwards that it has oxidized to some extent, due probably to exposing a certain amount of its surface when inserting the stem. A more satisfactory method for works use is to allow a supply of coal gas, without any air supply, to burn in the top of the crucible just above the surface of the metal. If this flame be of reasonable size, it will effectively protect the copper from any serious oxidation.

Another method of testing by means of the copper point is to use the lower temperature in the oxidizing atmosphere. Copper wire, of a reasonable gauge depending on the diameter of the stem (18 S.W.G. is suitable for most stems in common use), is wound over the hot-junction end of the stem for about a couple of inches, two layers being sufficient. This is then inserted in an open-ended electric furnace of the tube type, heated above the temperature required to melt copper. On inserting the copper-covered end of the stem the reading of the indicator will steadily rise as the stem heats up, until the copper starts to melt. A pause in the increase will indicate when this occurs, the pause continuing until all the copper has melted from the hot junction. The rise in temperature will then continue. The atmosphere in an open-ended electric furnace is sufficiently oxidizing to obtain the figure 1,065° C. If a quartz liner is in use in the electric furnace it should be removed before making such a test. Copper oxide is absolutely fatal to quartz. Within the last week I found copper oxide to be equally fatal to alundum.

A word of warning to anyone unused to electric furnaces for such testing would not be out of place here. There are few refractories which, either immediately or after some hours' heating at temperatures of 800° to 1,000° C., do not become, to some extent, electrical conductors. Alundum conducts directly it is heated to a red heat, and quartz will do so after several hours at 1,000° C. Should one side of the instrument be earthed by a metal case or for other reason, the instrument may get almost the full supply voltage across it. Due care must be taken to avoid such an occurrence

before either of the leads from the stem are connected. In other cases it may be found that while the effect is not sufficient to damage the instrument it may upset the readings.

It is a wise precaution to take two readings immediately following one another, one with the power switched on to the furnace and the other with it switched off. If there is any difference in the readings it is necessary either to make the tests with the power switched off or to take such steps as will effectively stop the trouble.

A simple experiment with an electric furnace will illustrate the importance of obtaining a deep insertion of a stem in a position where it relies on radiation and convection for the transference of heat from the hot body to the stem. The difference in the readings when comparing two stems of different types with an insufficient immersion often causes much trouble, but this may easily be overcome, once it is known to exist, by always using very deep immersion.

Nickel carbon eutectic.—In a paper recently read before the Faraday Society on "Pyrometer Standardization" the authors suggested a new freeze point, viz. that of a eutectic of nickel and carbon, the temperature being 1,330° C. To ascertain the suitability of such a test for the conditions laid down as the basis of this paper, a test was made in such a manner as could be carried out in any works using pyrometers. A quantity of nickel, in this case about 2½ lb., was melted in a small Fletcher Russell furnace. The couple used was of platinum platinum-iridium, one wire being covered with a small quartz tube, and the couple then inserted in another quartz tube of about ½ in. external diameter (if a larger diameter stem were used, more nickel would be required). Platinum and platinum-iridium couples should not be used at these temperatures; quartz sheaths were also found unsatisfactory. Readings of the E.M.F. generated and the cold junction were taken at the nickel point. No special precautions for exact cold-junction temperature control were taken. The elements of the couple were joined to the copper leads, the junctions being protected with adhesive tape and a thermometer being fixed in the same manner to indicate the temperature. Borax was used to keep the nickel from oxidizing. Satisfactory results being obtained for this point, a quantity of fine flake graphite was added to the molten nickel and the mixture kept molten for about an hour, graphite being added until it was in excess. Several freeze points were taken with this material, and the quartz tubes were perfectly satisfactory at this temperature. The couple was then further calibrated at the salt point. In this rough and ready manner the several points obtained for the freeze point of the eutectic were between 1,328° and 1,332° C. The precaution—an excess of graphite—which the authors of the paper say is necessary, was of course taken.

To test a pyrometer it is only necessary to note the temperature at which the pause occurs in the decreasing reading of the instrument when the mixture freezes.

The nickel point, 1,450° C., is one which presents some difficulties, and if an instrument were found to be accurate up to 1,330° C. it is unlikely that any serious error, except a mechanical trouble which would be detectable in other ways, would occur above this temperature. Pyrometers of the contact type are not often used above this temperature.

Numerous other metals and salts are quite suitable for this work, and an instrument required for accurate work over a wide range would be quite sufficiently tested by the use of:—

(1) Boiling-water point	100° C.
(2) Freeze point of lead	327° C.
(3) Ditto, antimony	630° C.*
(4) Ditto, salt	800° C.
(5) Ditto, copper in reducing atmosphere	1,083° C.
(6) Freeze point of carbon-nickel eutectic	1,330° C.
(7) Ditto, nickel	1,452° C.

When secondary fixed points other than those mentioned are used—and there are numerous ones which give satisfactory results—information as to the temperature should be sought from a *reliable* source.

Testing by sentinels.—Sometimes it is thought desirable to test a pyrometer by means of "sentinels." Peculiar results are sometimes obtained on doing so. When checking an instrument with sentinels or similar pyrometers, several precautions should be taken. The sentinel should not be put directly on the floor of the furnace; it is better put on a brick or some such material. Both the sentinel and the pyrometer stem should be protected against direct contact with the flames. Needless to say, both should be in one part of the furnace and not just as near one another as it is most convenient to put them.

Several other points may require attention.

The adjustment of the cold-junction temperature is frequently made in a slipshod manner, a thermometer being attached at the cold junction and expected to indicate the temperature immediately. It is always better to set the instrument pointer to the correct cold-junction temperature when the stem is disconnected, than to make an allowance after making the test. It is also preferable to test instruments with the indicators at a temperature as near as possible to that at which they are used. This is especially desirable with instruments having a high temperature-sensitivity coefficient.

When testing a pyrometer with a rare-metal couple, less of the stem will most probably be heated than when it is in normal use, causing it to read higher when tested at any particular temperature than it would for the same temperature when in use. This is due to the high temperature-resistance coefficient of the rare metal. The coefficient of nichrome being extremely small, this error is not sufficient to cause any trouble.

The immersion of one half of a 3-ft. stem made of nichrome would cause an error of 10 degrees at 1,000° C. with an indicator of 4-ohm resistance, but the same immersion of a platinum and platinum-rhodium stem would cause an error of 15 degrees with an indicator of 100 ohms.

Radiation and Optical Pyrometers.

Radiation and optical pyrometers are not open to such a wide range of simple rests. In fact, above about 1,200° C. direct comparison with a standard instrument

* This sometimes exhibits the phenomenon of delayed cooling. The maximum point of the rise is then 630° C.

calibrated in a well-equipped and reliable laboratory is the only method available in a works. In comparing two pyrometers of the same type against the same hot body, it is unnecessary to obtain "black body" conditions.

The interior of a hot enclosure kept at a uniform temperature gives true black body radiations through a hole in its side. From this it may be seen that the radiations received from the interior of a furnace, at an equal temperature throughout, obey the necessary conditions. Such are therefore obtained, very nearly, in most industrial furnaces.

When comparing a total radiation instrument against an optical pyrometer, black body conditions should be obtained. True black body conditions are not actually obtained, but a sufficiently close approximation is readily obtainable for the accuracy required when testing, as dealt with in this paper.

The lantern slide shows diagrammatically a cross-section through the centre of a furnace, readily constructed, which provides conditions sufficiently near to black body for most purposes. The Salamander crucible, 8 inches × 4 inches diameter internally, has a rectangular hole cut at the bottom about 1½ in. wide and 1 in. long. The remainder of the furnace, excluding of course the burner, is made from firebricks and fireclay, the bricks in this case being arranged so that it is only necessary to cut one brick. The burner used was taken from a small Fletcher Russell crucible furnace, and is normally supplied with gas at about 2 in. water gauge and air at 2 to 3 lb. per square inch. When the gas remains at 2 in. pressure a temperature of over 1,400° C. can be obtained in an hour. The maximum temperature obtainable depends to some extent on the inner surface of the crucible, higher temperatures being obtained as the carbon burns away and the surface starts to fuse.

The burner is so arranged at the front of the furnace as to give the gases a helical flow from the front to the back of the crucible, out from the hole at the back. The flame passing across the outside of the back of the crucible keeps it at a temperature so nearly that of the side that often no difference is appreciable to the eye at the lower temperatures. At the higher temperature the eye is dazzled and is not able to discern small differences. When using this furnace for total radiation pyrometers the burner must be put in such a position that it does not overlap the field of vision of the pyrometer. The diameter of 3 inches allows of testing any radiation pyrometer at a sufficient distance from the furnace to avoid damage to the receiving tube by heat. The gases must travel from the front to the back of the furnace and not largely exhaust at the front, as may be the case if the burner is not properly arranged, introducing the danger of fumes entering the receiving tube. If there is such a danger, and it should seem unavoidable, a draught of air across the front of the tube will, while not prejudicing the accuracy of the test, efficiently protect the tube. The fumes, if of water vapour only, absorb none of the radiated energy, causing erroneous readings, while some products of combustion may damage the mirror.

Flames, luminous or otherwise, in front of the hot body on which the tube is sighted do not appreciably affect the readings of a total radiation pyrometer as water vapour does.

This furnace is equally suitable for the comparison of optical pyrometers, except that luminous flames, if present, will influence the result owing to fluctuations in their luminosity between comparison readings.

RADIATION PYROMETRY CORRECTIONS, ASSUMING ENCLOSURE AT UNIFORM TEMPERATURE.

True temperature = 1,000° C. *L* = *depth of enclosure*, *d* = *diameter of opening*.

	In open	$d = L$	$3d = L$	$d = 10°$ deg.
Oxidized iron ..	50	5	0·6	0·15
Polished plat ..	84	8·4	1·0	0·25
Crucible clay ..	38	3·8	0·45	0·11

From the above figures it will be seen that if the temperature of this furnace be uniform at 1,000° C. the correction necessary for departure from black body conditions is only about 0·6 degree C., a correction which one can well afford to neglect.

If a standard instrument be not available for comparison the most satisfactory way of getting a test is to send the instrument to the makers or to the National Physical Laboratory.

For temperatures between 800° and 1,100° C., however, a test may be made against a thermo-couple. The thermo-couple should preferably be tested at a temperature close to that at which it is desired to test, or at which the radiation or optical instrument will generally be used. This makes the chance of error due to extrapolation small.

The salt point (800° C.) and copper point (1,065° or 1,083° C., depending on whether in an oxidizing or a reducing atmosphere) give two figures which will fix the calibration of the thermo-couple instrument. If a thermo-couple not generally used with an indicator be chosen for this work, the E.M.F. at the two points mentioned may be measured by a millivoltmeter or potentiometer and a curve plotted connecting E.M.F. and temperature. If a rare-metal couple be used an E.M.F. of the order of 10 millivolts will be obtained, but with a base-metal couple an E.M.F. as high as 60 to 80 millivolts may be generated. In plotting the curve between the two points the law

$$\text{Log } E = A \log t + B$$

is followed for the rare-metal couple, but a linear law may be assumed for the base-metal couple.

Some figures were published last autumn in several technical papers with regard to base-metal couples of nichrome and constantan or Eureka (a couple of these two wires is suitable for this test). In these it was mentioned that different couples of the same batch of wire could be relied on to 1 degree in 1,000° C. While this was true of wires obtained in this country before

the war, and possibly in America at present (the figures published being obtained by the Bureau of Standards), differences as high as 20 degrees C. are now obtained from different couples cut from the same coil of wire. The Eureka is the faulty member.

Having calibrated the couple, it is arranged with its hot junction just in front of some more or less plane surface, in a furnace, such that black body conditions are obtained, and the radiation or optical pyrometer can be focused on to the surface and thermo-couple through a hole in the wall or door of the furnace.

If a base-metal couple of large wires, say 9 or 11 S.W.G., is used, it is convenient and satisfactory to use them bare, but spaced a little apart, an inch or two at the hot junction end, the destruction of the couple in this case being a matter of little moment. Contamination of the elements, due to the burning gases, is quite negligible. Case-hardening compounds do, however, contaminate such unprotected couples very seriously. A brick in a muffle furnace, or the back of the crucible in the furnace previously described, form very suitable surfaces for the test. The furnace is run up to about the required temperature and allowed to become uniform, until the surface and the couple are at one temperature, as observed by being of uniform brightness, and readings of both instruments are taken. This is often most satisfactorily arranged by running to a higher temperature than is required and shutting the furnace down. Two observers are then an advantage, so that simultaneous readings are taken.

By this method, as the temperature slowly decreases, it is often quite impossible, when observing by eye, to discern the couple against its background. When such is the case the difference of temperature between the surface and couple is very small. If the conditions are closely akin to black body the difference would not be more than 1 or 2 degrees. This method is not applicable to higher temperatures, due to the difficulty in obtaining equal temperatures of the couple and focusing surface, even if the eye were not dazzled by the brilliance and unable to do the required matching.

A similar test may be carried out to much higher temperatures, using a rare-metal couple and an electric tube furnace, if such be available. Temperatures as high as 1,600° C. could be reached. With most total-radiation instruments the size of electric tube furnace commonly used is much too small to allow the necessary diameter of hot surface to be obtained. Many optical instruments could, however, be tested with the smallest of hot bodies.

To carry out the test the pyrometer is focused on one side of a body of small axial length; a piece of sheet iron is quite suitable, as a very near approach to black body radiation would be obtained. A calibrated rare-metal couple is pushed up to the iron from the other end of the furnace and simultaneous readings of both are taken after the furnace has reached a steady temperature, the correction, if any, being found from these figures. The couple must be protected against contamination by iron vapour. This test is described in more detail in a Bulletin of the Bureau of Standards on "Optical Pyrometry."

MOULDED INSULATING COMPOSITIONS.

By R. T. Fleming, Student.

(*Paper read before the* North-Western Students' Section, *at Manchester*, 5 *February*, 1919.)

Electrical engineering work may be divided into a great number of heads, and one of the most important features in the manufacturing branch is the insulation of electrical machines. The variety of materials employed makes the subject very large, and it is only possible to deal with one branch at a time. In this paper it is proposed to deal with the moulded class, i.e. a material made of a mixture of two or more ingredients, moulded in various shapes, and then hardened by the action of heat.

Early Work.

Until about 10 years ago the subject of moulded insulating compounds was very little known, and it is only recently that the subject has been sufficiently investigated to be put on a commercial basis. One of the most important and widely known branches of the industry is Bakelite manufacture, and this, or rather synthetic resin, was obtained as early as 1872. Since that date a great deal of research work has been undertaken and to-day the subject is becoming much better known. The very great difficulty in obtaining information on the subject is due to the fact that each manufacturer keeps his own process very secret, and only a general idea of the compositions and the methods employed in moulding can be given. The methods of manufacture, however, cannot vary a great deal in the essential points, and it is only in details that there are marked differences.

Moulded insulating materials have to withstand very severe tests in use, such as dampness, heat, or mechanical stresses. Very few compositions are able to fulfil all conditions and, at the same time, keep up a high standard of dielectric strength; it therefore happens that very often one quality has to be sacrificed in order to bring out another to any marked degree. Take the case of heat-resisting materials and more particularly arc-proof materials. A very high percentage of the composition consists of asbestos, thus gives the material its heat-resisting quality, but at the same time the dielectric strength of such products is very poor. Every class of electrical machinery and apparatus has various duties to fulfil and these duties make it necessary to place the finished products in various positions—for example, out of doors, in very hot places, down mines, and in other trying situations. Consequently, it is imperative that the component parts of such machinery, etc., should be able to withstand the ageing action of commercial usage.

Railway and tramway equipments are very good examples of the importance of having materials which do not absorb moisture.

Moulded Compositions: Raw Materials.

Moulded compositions consist of (1) binders, and (2) fillers.

Both organic and inorganic fillers are used; for example, organic binders for insulating purposes, and inorganic for heat-resisting properties.

The following are a number of materials which have been tried in connection with this work but, for various reasons, are now very seldom employed.

Alkaline silicates.—Attempts were made to employ these silicates as binders, but the idea has now been given up on account of the fact that moisture had the effect of softening the composition.

Hydraulic cement (Water mixed with asbestos fibre).—The chief fault was, as with many of the earlier compositions, its inability to be moulded to any complex shapes.

Ox-blood and wood-pulp composition.—This material was obtained by treating the blood to obtain its fibrine, which was dried, powdered, and mixed with fillers. The fact that this material is not so readily moulded or as chemically stable as shellac, has made it rather unpopular.

Casein, chemically treated to convert it into a hard substance, has been used, but its inability to withstand moisture has limited its usefulness from an electrical point of view.

Sulphur has been employed as a binder, but the acids resulting from oxidation were fatal to its success.

Papier mâché.—This material is still used to a great extent, being sheets of specially prepared stiff paper, which stick to one another by aid of glutinous substances.

Cabinet-maker's glue has been used as a binder. The products are generally treated with formaldehyde, chromates, or other chemical agents, to render the glue waterproof and chemically stable. No process, however, was developed which would accomplish this on animal glue.

Cellulose and celluloid were experimented upon to render them less inflammable. The materials made had great success in many branches of industry, but were no use from the electrical point of view.

Paraffin and vegetable waxes were used as binders, but the failure in this case was due to the low melting point of the waxes.

Salt and marble, with suitable binders, are still used to a very small extent.

Turf has also attracted attention. The poor heat-resisting qualities of the substance, however, have made it of no practical use. The interest in turf was due to its low cost and its wide distribution of fibrous structure.

Table 1 gives a list of all the most important materials which are employed in the manufacture of moulded pieces. Both binding and filling mediums are shown.

TABLE 1.

Raw Materials employed in the Manufacture of Moulded Compositions.

Asbestos	Hemp	Linseed oil
Clay	Flax	Chinese wood oil
Mica	Asphalt	Soya bean oil
Silica and its compounds	Shellac	Poppy seed oil
Hydraulic cement	Rubber	Rosin oil
Alkaline earths	Phenol carbolic acid	Turpentine
Vegetable fibres	Dammor gum	Benzine
Camphor	Resin	Alcohols
Wood pulp	Paraffin wax	Tar
Cotton		Pitch

Formaldehyde and various condensation products.

A good knowledge of the properties of the raw material gives the key to the use to which the final product can be put. Only the most important materials will be mentioned, as there are so many which can be employed.

ASBESTOS.

The term "asbestos" is one which is very freely and loosely used, being applied to a great number of crystalline minerals having a fibrous structure. A great number of these so-called samples of asbestos, however, are not able to withstand the action of heat and acids to the same degree as the real material. Chemically, asbestos is a silicate of magnesia.

The following figures show the results of analyses carried out on three samples of asbestos and give a very good idea of the type of material employed in the manufacture of moulded pieces.

	A	B*	C*
Silica (S_2O_2) ..	38·8	48·8	54
Magnesia (MgO) ..	42·4	20·0	26·6
Lime (CaO) ..	1·79	10·0	5·8
Ferrous oxide (FeO) ..	1·61	22·0	12·6
Alumina (Al_2O_3) ..	1·07		
Moisture (H_2O) ..	14·33	—	—
	100·0	100·8	99·0

These asbestos materials cannot be considered to be acid-proof, as even weak acids or alkalis will have some action on many forms of asbestos. One of the most noteworthy characteristics of this material is its power of absorbing liquids. The property may be well used when organic binders are forced, by the pressure of moulding, into the capillaries of the asbestos, thus making almost a homogeneous material. On the other hand, moisture is also easily absorbed, which is the worst point about products of this nature.

* B and C are analyses of samples of asbestos taken from a moulded article, and may contain some other filler.

SHELLAC.

This material is obtained from natural sources. It is an animal product discharged from the bodies of insects. The lac is produced by the female to protect the eggs. Trees are covered with these insects and to prepare the substance known as shellac, twigs are broken off and the lac removed by rollers. The crude substance is red and contains from 60 to 70 per cent of resin. When taken from the trees the substance is known as stick-lac; and when crushed the second product is known as seed-lac. This seed-lac is placed in a bag and warmed in front of a charcoal fire, until the material melts and drops through. This is the final product, which is rolled into sheets and is known as shell-lac or shellac.

The material comes upon the market under the following names: Stick-lac; seed-lac; shellac; button lac; garnet lac.

RUBBER.

This substance is a vegetable product, the liquid caoutchouc, or crude rubber, exuding from notches made in trees. For commercial purposes, rubber is usually vulcanized by the incorporation of sulphur. The introduction of this material makes the rubber harder and the use for which the final product is intended has to be taken into account.

The other materials mentioned include asphalt, tar, pitch, oil and formaldehyde products. The former are all well known and do not require any further explanation; the last mentioned will be dealt with later (see Bakelite).

VARIOUS TYPES OF MOULDED COMPOSITIONS.

The various types of moulded compositions may roughly be classified as follows:—

(A) Bakelite.
(B) Moulded rubber.
(C) Asbestos.
(D) Shellac.

Each class is better suited for one particular type of work than another, and Table 2 shows the most important points.

TABLE 2.

Material	Temperature-resisting Properties	Dielectric Strength: Volts per mil	Moisture Absorption
A	Stands 100° to 200° C.	(Medium) 200	Very good
B	Stands to 100° C.	(High) 400	Good
C	Stands red heat	(Low) 100	Bad (7 %)
D	Stands to 70° C.	(Medium) 250 to 300	Medium (between A&B)

The above classification includes only four types of materials, but the following more complete list is given

by Hemming. This does not really include much more than the abbreviated list.

(1) Organic hot moulded materials.
(2) Organic cold moulded materials.
(3) Inorganic cold moulded materials.
(4) Ceramics.
(5) Rubber compounds.
(6) Organic plastics.
(7) Synthetic resinous products.
(8) Hardened fibre materials.

In Hemming's list, classes (1), (2) and (3) do not give any information regarding the component parts of the finished material, but rather the method of manufacture.

Class (4) Ceramics is a very important branch of moulded insulation work, but does not come within the scope of this paper, porcelain, slate and lava products being quite distinct from any of the substances here considered.

Of organic plastics (class 6) useful for insulating work, celluloid comes first, and its use in the electrical industry is very limited on account of its very poor heat-resisting qualities and great inflammability.

Casein products may be placed in the same category. Although these materials have much better heat-resisting qualities than celluloid, yet they will not withstand moisture to any great extent. The uses to which these materials are mostly put are in the manufacture of ornamental and other articles, such as combs, pipe stems, buttons, etc., and they can be made in almost any colour.

Hemming's class (7) corresponds to type (A) above, whilst class (8) comes outside the scope of this paper.

Bakelite and Synthetic Resinous Products.

Type (A) materials are one of the most important of the moulded compositions, and the method of their manufacture should be clearly understood. Before these products had been discovered, hot moulded organic substances were used to a very large extent in their places, but they were not entirely satisfactory, their chief fault being their very low melting points, shellac being almost universally used as a binder. The synthetic resinous products, or phenol-formaldehyde products, not only possess all the good points which the earlier organic compositions had, but also have a much higher melting point and possess very good heat-resisting qualities. They have, however, one very serious drawback, namely the high cost of production, which limits their use in all places except where absolutely necessary. Lately, however, some makers claim to make them as cheaply as other plastics.

The good qualities of these products are due to the binding agent, which is a synthetic resin formed by the chemical action of phenol on formaldehyde, heated under proper conditions. The reaction takes place in the presence of a catalyst which is usually a small amount of alkaline substance. The condensation products of this reaction are known as "Bakelite" after the discoverer, Dr. L. H. Backland.

These products may be grouped under three heads, known as Bakelite A, Bakelite B, and Bakelite C.

Bakelite A is the first condensation product, and is produced by getting rid of most of the moisture. Bakelite B, the intermediate product, is a higher anhydride. The final product, Bakelite C, is a very hard mass which may be prepared in either an opaque or transparent form. This substance withstands the action of most chemicals, except boiling sulphuric acid (conc.) and boiling nitric acid (conc.), which destroy it. It can stand a temperature of 300° C. and also any machining, but, strictly speaking, this material is not a plastic because heat will no longer render it soft.

For all practical uses, the A product is used as the raw material. This can be obtained in either solid or liquid form, and in the case of moulded compositions the Bakelite is then mixed with the filler which is going to be used. In some cases the process is started with Bakelite B. This has certain advantages which will be described later.

The final object in moulding Bakelite pieces is to obtain a piece in the C variety. This grade not being a true plastic, the moulding has to be done in the earlier stages, and the material is finally converted into grade C by means of "Bakerlizing."

In some cases the material is changed from grade A to C in one operation; in others, first from A to B, and then the piece is removed from the mould and the process of converting it to C is started. To obtain the best results the compounds should be heated at comparatively high temperatures (for this type of material about 150–160° C.) under mechanical pressure, as when they are raised above 100° C. under atmospheric pressure gases are evolved which force themselves out of the mass, causing it to become spongy. This makes the final product practically useless. To overcome this trouble, the material is heated under sufficient pressure to counteract the action of the gases.

The piece of apparatus in which this process is carried out is known as a "Bakerlizer." This consists of an oven in which the objects are placed, having a steam jacket and fitted with a pump which produces pressure in the interior. This pressure is usually about from 100 to 130 lb. per square inch. The temperature of the inner chamber depends very much upon the filler used. For instance, if asbestos is used to mix with the Bakelite, high temperatures may be reached without any detrimental effect. If, however, wood pulp or similar materials be employed, the temperature of "Bakerlizing" must be kept lower, in order not to char the organic filler. For mineral fillers, 200° C. is a very usual working temperature.

Moulds and Dies.

Moulds and dies play a very important part in the manufacture of moulded compositions, and great care should be taken in designing these pieces of apparatus, as any unnecessary complications in the shape of the mould make matters very difficult. In the first place the price of the mould is greatly increased and there is a risk of the final pieces not being well moulded, since any intricate parts may soon wear out and will cause burrs along some of the edges. When these facts are borne in mind a great deal of trouble to both

the manufacturer and the consumer can be saved. Another point against the use of complicated moulds and dies is the limit which they set to the choice of material. There are so many compositions which can be moulded into simple shapes, but when the finished article has such items as holes, irregular surfaces, etc., only material which becomes very soft or liquids can be forced into the interstices. The nature of the material used has a great deal to do with the length of time a mould will last, some substances wearing away the metal at a much greater rate than others. When the dies or moulds show any signs of wearing they should at once be fitted with new working parts, always in first-class steel. Should repairs and attention be neglected the result will be inaccurate pieces.

In moulding these materials there are two types of mould used known as (1) open type, and (2) closed type.

The open type consist of two flat pieces, one or both being recessed. These plates come together and press the material into the desired shape, and there is always a groove round the edges of these moulds into which the excess of the material is squeezed. In operation the die is heated and when complete the whole is cooled and the piece removed.

The closed variety consists of a box and plunger. The material is placed in the box and the plunger is then forced down. Usually the moulds are fitted with two plungers, an upper and lower one, the bottom one acting as an ejector when the operation is complete.

Metal pieces can be incorporated in the moulds and are so placed as to enable the composition to get a firm hold.

Testing and Properties of Materials.

One of the most important points to consider in connection with moulded compositions is the life of the product and all the various requirements which will be expected of it.

The class of moulded insulation which most nearly fulfils all conditions is the "ceramic" class, with which we are not dealing.

Manufacturers claim various qualities which their materials possess, and it is very necessary for the consumer to find out whether the samples come up to the makers' claims. There are various opinions as to how these materials should be tested, but up to the present in this country no standard tests have been given, although leading electrical bodies have devoted a great deal of time to the subject. In America, a Committee in connection with the Associated Manufacturers of Electrical Supplies have issued a bulletin which gives a very good set of tests.

The number of tests to which a composition may be subjected are as follows:—

(*a*) General characteristics.
(*b*) Heat tests.
(*c*) Dielectric strength.
(*d*) Absorption tests.
(*e*) Mechanical properties.
(*f*) Effect of chemicals.

The first on this list is only a matter of close inspection, to discover such things as colour and what method has been used to give the material its finish. Very often when giving the material its preliminary examination the brittleness and hardness are ascertained by any simple method such as cutting or bending. The whole of this part of the investigation is done with practically no apparatus, and it gives an idea as to the subsequent course to adopt, more than anything else.

Heat tests.—These are divided into a number of sub-heads, such as softening point, flame tests, exposure to heat for long periods, etc. The softening point of a moulded material is of very great importance and, at present, rather crude methods are employed to determine it. One method, used very frequently, is to suspend the sample in a beaker of water and then raise the temperature, taking care to squeeze the material every few moments, until it slightly yields to the pressure; at this point the temperature is noted. This test is very approximate, but if care be taken the results obtained are quite useful from a commercial point of view.

In the standard tests set out by the American Associated Manufacturers of Electrical Products, the nearest approach to a softening point determination is the test for distortion under heat. This test requires a special piece of apparatus which consists of two steel supports upon which is placed the test-piece. These supports are 100 mm. apart, with the load applied vertically and midway between them. Various weights can be placed on the test-piece 5½, 11 or 22 lb. The piece undergoing the test is placed in an air bath surrounded by an oil bath, the temperature of which is raised. Thermometers and measuring gauges are included in the apparatus, and the distorting point is considered to be the temperature at which the moulded piece has deflected 10 mils at the centre.

Tests are also carried out to ascertain if the material will support combustion and whether it will burn in a flame or remain inert. These tests are very important when the material is going to be used as arc shields, or in any position where it is likely to come in contact with a flame. This test is usually carried out by placing the specimen in a flame and observing its behaviour. The worst kind of material for arc shields and the like is that which continues to burn when the source of ignition has been removed. Material which burns only when the flame is present is much less dangerous.

After the softening point and flame tests have been carried out, the next investigation is to see the effect of continual heat upon the specimen. The usual method employed is to place the sample in an oven at 200° C.; after a few minutes the specimen should be examined to see if the heat for such a short period has had any effect and also in what way the material has been affected. After this preliminary examination, the material is replaced in the oven and again examined at the end of one hour. After this period, the sample should be looked at every few hours until the total time of heating has reached 24 hours. If a sample becomes very plastic or badly defaced it is quite unnecessary to continue the test for such a length of

time, in fact very few classes of materials, with the exception of some phenol formaldehyde products, will be able to stand up to this test. The effect of steam on compositions is frequently tested, but if satisfactory heat and absorption tests are carried out, the former is not really essential.

The tests which have been described are quite sufficient for commercial purposes. When scientific research work is to be carried out, other tests might be added, such as the coefficient of linear expansion, and thermal conductivity. The classes of material which withstand heat in the best manner are the inorganic cold moulded and the synthetic resinous products. These materials are used in arc shields and will stand high temperatures, although when the composition reaches 600° C. it is very likely to become affected, as the water constituents are liable to split up. This will happen only if maintained at a high temperature for too long a time.

Dielectric strength.—The dielectric strength of all the materials has to be tested with the material in various conditions: first, as it arrives from the makers; then other specimens after immersion in water; and, lastly, after immersion in oil. It is necessary to perform these tests, as the material may be required to put up with either of these conditions, and if the liquids attack any of the ingredients of the composition they should be avoided. The dielectric strength of moulded compositions varies a great deal with the class of materials employed. The moulded rubber products give the best dielectric results, 400 volts per mil being a good average value. The majority of other moulded compositions do not give very much more than 200 volts per mil.

For carrying out this test a special test-piece has to be made, having a thin wall at the top which gradually becomes thicker on the way down. The bottom is made quite flat, frequently having the maker's name moulded in the circumference. The cup is usually about 2½ inches high with a base of 2¼ inches diameter.

Various methods are employed in carrying out the breakdown test. One method is to place the test-cup upon an earthed metal sheet and a well fitting metal plug inside, and then to apply the voltage. Another method is to float the cup on mercury and pour a little inside, thus ensuring good contact. Both these methods are often adopted and are very satisfactory, providing that the breakdown voltage is low enough not to flash over the side of the cup. If this does happen, it is necessary to adopt another method of procedure, and the one which is used is to immerse the cup in transformer oil and then follow the same course as before. Even with the test piece under oil it is often advisable to insulate the wire leading to the inside of the cup in order to prevent breakdowns across the oil between the terminals.

It is not infrequent in work on a commercial basis that a breakdown value has to be taken in a hurry on some sample of material, and in such cases one is unable to have test-cups for use and the breakdown has to be taken on any convenient spot in the sample. These are very often so small that it is almost impossible to get up to a sufficient voltage without a flash over. Samples are then sometimes ground thin to enable a value to be taken, but results obtained in this manner are not at all satisfactory and very erratic.

Chemical tests.—These are for ascertaining if the material absorbs moisture and also the effect of various liquids upon it. The most important of these tests is the determination of the percentage of water absorbed in a given time. For this work any small piece of the material may be used, although usually a test-cup, as for the dielectric test, is adopted. The sample is kept warm in an oven, then weighed; after this it is immersed in water (distilled, for preference) and allowed to remain for the period desired. The most usual length of this test is either 12 or 24 hours. The results should contain the following figures: (*a*) Original weight of sample; (*b*) dry weight; (*c*) saturated weight; (*d*) percentage moisture absorbed in .. hours.

Tests are also carried out by immersing samples of the moulded article or test-cup in hot oil at 70–80° C. for about 6 hours. The chief object of this test is to observe the effect of the oil on the surface, and, as mentioned before, the effect upon the dielectric strength of the sample. The effects of hot oil are very varied, but usually a slight increase of weight can be observed, and in a great number of cases the surface becomes soft and slimy. The remaining immersion tests are to find out the effect of acids or alkalis. The samples are usually immersed for 6 hours. The acid used most often is sulphuric of specific gravity 1·4, and the alkali, a 20 per cent solution of sodium hydroxide. Discoloration is a very common result of this test.

Mechanical properties.—The mechanical properties of moulded materials are of vast importance. There are so many places where the final products can be used that the makers have to realize that their pieces may have to withstand varied kinds of stresses, compressive, tensile or shear. It is very necessary to insist on these tests being taken, and at the same time it should be observed how the material stands up to a machine tool and dies for cutting threads, etc. Wherever it is possible, machining is not done, as the moulded pieces can be made with very great accuracy, but even now it is very often necessary. However, it is essential that these properties should be investigated when the other tests are being done. The stresses to which the material is subjected, are as follows: (*a*) Tensile strength; (*b*) compressive strength; (*c*) transverse strength; (*d*) shear strength; (*e*) effect of impact. Any ordinary testing machine can be employed for this work, provided that it is sensitive and does not apply the load at too great a rate. Some authorities state that the weight of loading should be between 3 mm. and 6 mm. per minute, but good results can be obtained with loading at rates as high as 9 mm. per minute.

Tensile tests.—For tensile testing there are two kinds of test-pieces used. The first type is either moulded or cut out from a sheet of material, and is the same shape as that used on strip metal. If the sample is cut from a sheet, great care must be taken to have even edges, especially on curves.

The specimen is cut having broad ends and waisted in the middle. There are no particular dimen-

sions for this type, as the shape has not been standardized. If the sheet of the material is large enough, a test bar of total length of 18 inches having 3 inches each end for gripping and a 12 inch test length, is a very good size, the curve radius in this case being 3 inches, which is quite large; the smaller this radius, the greater is the risk of the specimen breaking at the neck. The question of samples breaking at this point is very important, because if it should occur it makes the measurement of elongation impossible, and with elastic materials this question is one which has to be fixed. In fact, test-pieces of this class are not very satisfactory on this account. Their chief advantage is that they can be adapted to the ordinary type of friction grips which are always supplied with testing machines. The second shape of tensile test-piece is the same style as is always used in testing cement blocks, and it is this shape which has been adopted by the American Committee. This test-piece can most easily be described as a solid figure 8; special grips of hardened steel have to be made for this shape. This method of testing the tensile strength is more satisfactory than the one previously mentioned on account of the fact that the breaking point is bound to occur in the correct place, also the test-pieces are $\frac{1}{2}$ inch thick and hence the figures obtained are a better average value than those taken from a thin sheet.

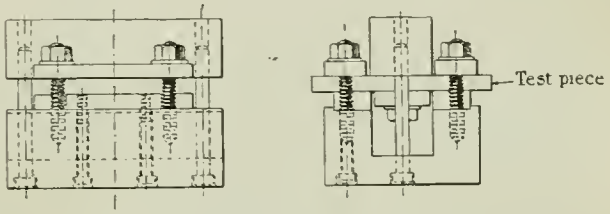
Tensile tests are taken with the material under various different conditions, in order to see how the strength is affected. Samples are heated to a temperature a few degrees below their softening point and pulled while hot, also specimens which have been immersed in water for certain periods of time are subjected to similar treatment. The results of the tests can be given as desired; usually figures are stated per square inch. It is impossible to give any figures of the tensile strength of such materials, as the differences are very great and vary from a few hundred pounds up to as high as 40 tons per square inch.

Compression tests.—The only satisfactory shape of specimen for compression tests is a cube. The size of the cube does not matter a great deal so long as it is of ordinary dimensions. The most usual form, of course, is to have a 1-inch cube. The rate of loading and treatment of test-pieces are the same as in the case of the tensile pieces.

Transverse test.—The best samples for transverse testing are those adopted by the American Committee. The test-piece is in the shape of a rectangular block 5 inches $\times \frac{1}{2}$ inch $\times \frac{1}{2}$ inch. This is supported on centres 4 inches apart and the pressure is applied in the middle of the span by a wedge-shaped compression grip. The load is applied in the usual way until the specimen breaks. The results are given in terms of fibre stress per inch, that is, the stress in the fibre which is calculated from the formula $S = \frac{3\,P\,L}{2\,B\,D^2}$,

where S = fibre stress,
P = load,
L = distance between supports,
B = width of test piece,
D = depth of test-piece.

Shear.—The test for shearing moulded compositions is not very often done, but some good results have been obtained on the following apparatus. The test-piece, which is a rectangular slab about 5 inches $\times 2\frac{1}{2}$ inches, is bolted by means of a steel piece, or to another steel block, so that an equal amount projects at each side. This is then placed on another steel block, which consists of two pieces mounted on a base, having two pins in it to guide the original block. The first block is then placed on the double-sided base, so that the test-piece rests on the edges. When pressure is applied to the top block it forces it down between the two, at the same time shearing the specimen at each side. The area sheared is then measured and the result given in pounds per square inch. The arrangement of the apparatus is shown in the diagram herewith.



Shear test apparatus.

Impact test.—The effect of impact is tested in the same manner as with metals, on notched specimens.

Admiralty heat test (special test).—In this test a certain length of moulded composition is clamped at one end, leaving the other end protruding, thus forming a cantilever. This is placed in an oven for two hours at 70° C. At the extreme end of the arm a weight is hung, and the total permanent deflection is measured. The amount which is allowed varies with different specifications.

The tests which have been mentioned include all the important methods, and other special tests sometimes carried out are not worth mentioning because they vary with the sample in hand. It is very often necessary to get some details of some property of a composition in a short time, in which case the tests have to be carried out on the moulded piece itself, and from this fact it can easily be seen that each test is different from others.

CABLE TESTING IN MINES.

By E. A. Guthrie, Student.

(*Paper read before the* North-Western Students' Section, 5 *March*, 1919.)

General.

During the past few years much has been written, and still more has been said, on the subject of "Cable Breakdowns and Cable Faults in Mines," but the matter is one of the uttermost importance owing to the increase in the demand for electricity for mining purposes and, in the case of alternating-current systems, to the higher voltage now used in many mines in this country and abroad. In most cases cables do not give much trouble, and the majority of cable breakdowns that do occur arise from most simple causes and could easily be avoided if installations were installed with care and skill and tested from time to time.

Cable Faults.

Cables are always tested before leaving the cable factory, so that the chances of a manufacturing fault being overlooked before despatch can be considered to be practically nil.

It is subsequent to installation, during installation, and while connecting up that cable faults are most likely to occur, and these may be considered in detail.

Subsequent to Installation.—Under this heading, causes leading to trouble may be considered to be (1) mechanical damage; (2) electrical effects; (3) chemical action.

(1) Mechanical damage in transit, etc., calls for no comment other than the importance of careful and systematic testing to detect such damage should it exist.

(2) Electrical troubles may occur from excessive voltage, excessive current, leakage current, and external heating.

Excessive voltage.—Under the conditions which are usually found in mines it is improbable that pressure-surges will reach such a value as to damage the cables, but in some remote and exceptional cases lightning striking apparatus on the surface of a mine appears to have damaged cables and apparatus underground.

Excessive current.—The factors which determine the permissible overload on cables are variable and numerous, and render it necessary to consider each case on its individual conditions. Breakdowns due to overload troubles have been known but only occasionally, and very rarely take place.

Leakage current.—Leakage current troubles have been found to take place from leakage from the conductors contained in the cable itself, and in some cases from external sources. Leakage currents give rise to secondary effects which in many cases prove serious.

The question of earthing, conductivity of earth conductors, and automatic electric protection [Regulations 125*a*; 125*b*; 129*e* (iv) and 128*c*] are all matters so inseparably interwoven that they may be considered collectively in connection with this paper. The objects aimed at are prevention from shock, open sparking and overheating. In dealing with concentric systems, current on exposed conductors should be restricted to a minimum, say to that necessary for operating switches on some leakage-protection arrangement.

If a whole system can be automatically and instantaneously made "dead" when a leakage of current of considerably less than 1 ampere takes place, it follows that damage due to leakage-current effects would be reduced to practically nil. Also the Regulations dealing with the conductivity of earth conductors might be worth reconsideration—the question of mechanical strength being of course on quite another plane.

Protection from shock to a large extent depends on sound earthing. In the early days of the use of electricity in mines, earthing was effected by sinking local earth-plates wherever a motor was installed. Later, the essential factor was to earth the electrical system at one point—the midvoltage point of a direct-current system, or the neutral point of a polyphase system. A system of automatic leakage protection is now used in most mines and supersedes the old methods.

It will readily be appreciated that earth protection systems should be frequently tested and inspected.

External heating.—Probably one of the most prolific sources of trouble in cable installations in connection with mines comes from external heating. In some instances cables have been carefully laid underground between the supply station and the mine and have been found to be damaged owing to steam or exhaust pipes being laid near to or across their track; and for this reason in many instances overhead cables are used between the supply station and the mine. Such overhead cables are usually installed by being slung from a suspension rope.

(3) *Chemical action.*—Electrochemical action takes place in the development of most cable faults, but can be considered to be a secondary effect in the development of the large majority of cable troubles, and it often destroys all evidence of the primary cause of a fault, thus tending to lead the investigator to a mistaken conclusion.

Effects of Cable Faults.

During installation.—One of the chief mistakes inexperienced men make when handling cables is that they

do not appreciate that cables will not stand twisting. Most cables will stand a fair amount of rough handling and some degree of bending. The most prevalent source of trouble is twisting, and during the installation in mines of shaft and roadway cables every care must be exercised to ensure that no " twisting " or " kinking " takes place, as otherwise trouble will probably occur when the cables are tested before being placed in commercial service.

Cables have often to be installed under severe and, in most cases, unfavourable conditions; for example, roadway cables are often extremely difficult to handle and install. In such cases cable-sagging and dragging along the ground should as far as possible be avoided.

Often in mines a number of men have to carry a cable some distance underground over rough ground and around corners, and in such cases twisting would possibly occur if great care is not taken.

If, when unreeling, a bight on the cable is caused, it should be removed by carefully reversing in order to avoid " kinks " which damage the cable insulation and the armour.

In some cases it is found necessary to unwind the cable from the drum and to carry the cable forward as it is paid off. This is owing to the small head-room generally to be found in mines. Assuming that the method used in a particular case is to unwind the cable at the pit bottom, probably the quickest and simplest way to place the cable in position is to lash it to tubs spaced a convenient distance apart. The nose of the leading cable or tub could then be fixed to a haulage rope and the cable run forward in this manner to the position in which it is to be installed.

Connecting up cables.—Leakage currents have been found from trims at cable terminals owing to tapes of hygroscopic material being left in contact with bare conductors, and this emphasizes the importance of great care being taken as regards detail effects when connecting up cables.

Joint boxes, etc.—Owing to the Mines Regulations naked lights are not permitted in most mines and it is therefore necessary to use clamp-type connections. These should be designed to clamp as many individual wires as possible. Care should be taken to ensure that the wires are well cleaned, since dirty wires are very often a cause of trouble in conductor joints. Each individual conductor joint is usually protected with sleeves or insulating tape.

Joint boxes are usually filled with a special compound which is poured into the box at a fairly high temperature after the cables have been connected up, and where naked lights are prohibited it is necessary to carry the hot compound in a specially designed bucket from the place of heating the compound to the joint box. The compound should be poured into the joint box at a specified temperature since, if overheated, excessive air bubbles will be formed within the box, apart from the fact that joint boxes are designed to minimize the trapping of air.

To conform with the Mines Regulations efficient electrical contact must be made on the armouring of cables, and for this reason jumper connections are fitted across the joint boxes.

Cable Testing.

The object of testing is to anticipate breakdowns in the incipient stage. In this respect it is recommended that tests be taken, recorded, and compared systematically at prescribed intervals, say daily, weekly, etc. If convenient the tests should be taken under similar conditions.

Insulation resistance.—With the lengths of cables usually met with in mines, test sets of the " Megger " type are generally suitable for routine insulation testing. In a test of this nature the pressure should be kept constant throughout the test. Also the testing leads should be themselves tested from time to time for insulation resistance and continuity.

A method of testing high-tension alternating-current cables is shown in Fig. 1.

A high-tension electrostatic voltmeter is inserted in the connection to earth when the switch is on " B "; and when the switch is on " C " a low-tension alternating-current voltmeter or ammeter is substituted for the electrostatic voltmeter. From the two readings the leakage from the cores is indicated. When the switch is on " D " a battery and insulation-resistance testing

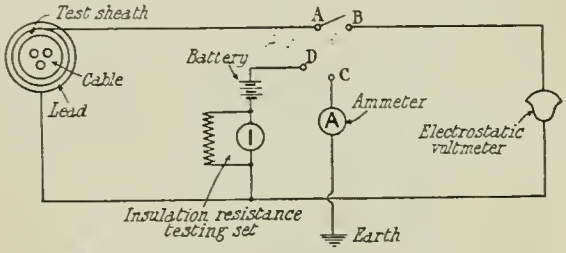


Fig. 1.—Method of testing high-tension alternating-current cables.

set is connected between the cable test-sheath and earth. The condition of the insulation over the sheath is in this way examined, and any exterior damage to the cable becomes apparent.

Flash test.—While it is admitted that most tests are important the author is of the opinion that the " flash test " is the most reliable.

Regulation No. 124 of the Coal Mines Act, 1911, provides that:—

> " A pressure test to earth and between conductors equivalent to at least twice the maximum working pressure should be applied as far as practicable to all apparatus intended for use below ground. The same test should be applied in the case of repair apparatus before it is again put into service."

In many cases the above test is considered to be impracticable, perhaps because it is not generally known that there exists a device for carrying it out. The rule may, however, be readily complied with by a simple and portable unit, known as a variable-ratio transformer of the Cowan-Still pattern. The apparatus consist of an alternating-current induction regulator specially designed for colliery service below ground.

In all high-voltage testing, control of the secondary pressure of the step-up transformer is essential. If the

method adopted is that of field variation of the supply alternator, a very wide range of control is necessary, with the attendant evils of a weak field at low generator pressures. The results are distortion of the generator wave at the transformer terminals, and the establishing of unstable conditions. Voltage control should, therefore, always be effected by means of a variable-ratio transformer, in which case the generator may remain fully excited and the necessary pressure variation be secured by the simple rotation of the primary of the variable-ratio transformer.

The importance of a gradual rise of pressure for cable testing cannot be over-estimated. It is by no means uncommon practice for the full testing pressure to be immediately applied when testing cables in mines, with the result that the material under test is subjected to undue stress.

Lack of suitable testing plant leads in many cases to

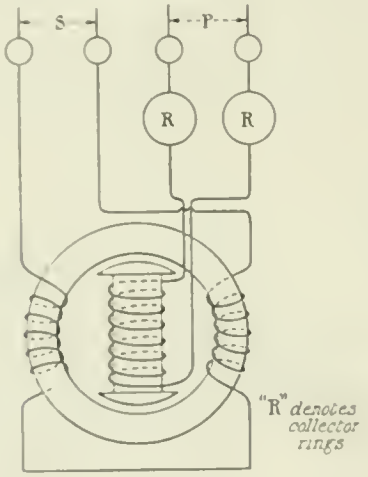


FIG. 2.

avoidable breakdowns and disastrous interruptions in the supply. The cables must be tested in conformity with Government regulations, and frequently a step-up transformer provided with a number of tappings is the only testing apparatus available. Severe conditions must, if necessary, then be imposed when the full pressure is immediately applied, the numerous breakdowns directly attributable to this cause bearing evidence of the unsuitability of the tests imposed.

The only practical safe means of testing and completely avoiding all undue strain is to apply a gradually varying pressure from zero to the maximum desirable value, such control being readily effected by the use of a variable-ratio transformer.

Induction regulators are variable-ratio transformers suitable for cases in which a gradually varying pressure is required. They are usually of the single-phase pattern, although capable of being arranged for three-phase operation.

The induction regulator has two windings, the primary connected directly across the supply, and the secondary in series with the cable to be tested. The pressure is applied from the available source of supply and, by means of the induction regulator, is gradually raised from zero to double the working pressure on the section of cable under test (see Fig. 2).

The primary winding is arranged on a movable iron core, somewhat resembling that of a two-pole shuttle-wound armature. The core is built up of the best quality sheet-iron laminations and mounted on a suitable shaft carrying the necessary slip-rings to enable connection to the windings to be effected.

The series, or secondary, winding is arranged in slots on the inner circumference of the stationary core, and the movable core with the primary winding can be rotated round an axis coincident with the axis of the cylindrical fixed core, the position being adjusted either automatically or by means of a hand wheel and worm-gear.

All variations effected in the supply pressure are entirely due to the change in the angular positions of the two cores. For example, when the primary is in a vertical position the primary flux passes through the secondary coils in such a direction that the maximum secondary electromotive force is induced. This electromotive force either may assist the line pressure, in which case a positive boost is effected, or may directly oppose the line pressure, a negative or reverse boost then resulting.

The direction of the boost depends upon the polarity of the windings, since the windings on both cores are in effect polar windings. Thus with a given pole of the primary opposite a similar pole of the secondary a positive boost is obtained, whereas when unlike poles face each other a negative boost results. When the primary is in a horizontal position the secondary voltage

FIG. 3.

is zero and the regulator has no effect on the line pressure, while between this position and either of the two maximum positions any desired boosting effect can be obtained.

It will be apparent that this arrangement gives a much finer regulation than is possible with any other form of regulating device, as the voltage is adjusted not in definite steps but as gradually as may be desired.

Induction regulators for use in mines are supplied in the oil-cooled pattern. The regulator is completely enclosed in a strong case and the operation is effected by means of a hand wheel placed in a convenient position on the outside of the case. Contact is effected with the fixed and rotatable secondary portions and with the secondary circuit by means of slip-rings and brushes so designed as to be incapable of breaking the circuit under any circumstances, and this is of course an important feature in connection with mining work.

The regulator secondary voltage may attain any desired maximum value within reason, bearing in mind the mechanical construction of the apparatus, and the present practice is to fix an upper limit of 6,600 volts. Since cables are usually tested at double the

working pressure, higher secondary voltages than 6,600 are seldom required when testing in mines, but if a higher testing pressure is desired this can easily be arranged by placing a step-up transformer having its primary designed for, and connected in series with, the secondary of an induction regulator as shown in Fig. 3, in which S = supply mains, A = induction regulator, and B = step-up transformer.

Assuming the supply pressure to be 500 volts and the step-up transformer to have a ratio of 10 to 1, it follows that by means of the induction regulator a testing voltage of 10,000 can be got on the secondary side of the step-up transformer, and, further, this voltage can be varied gradually from zero to 10,000 volts.

When a step-up transformer is necessary the induction regulator is connected between the supply and the low-tension side of the step-up transformer. The supply pressure to the low-tension side can be varied from zero to the maximum voltage, and thus on the high-tension side of the step-up transformer the pressure is varied betweeen zero and the full voltage it is capable

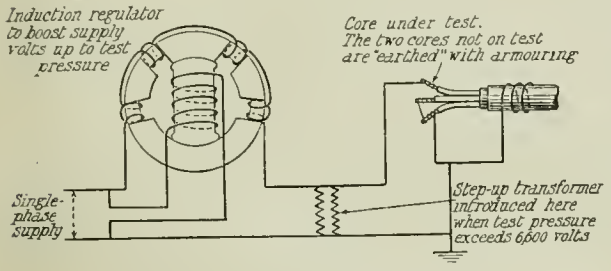

Induction regulator to boost supply volts up to test pressure
Core under test. The two cores not on test are "earthed" with armouring
Single-phase supply
Step-up transformer introduced here when test pressure exceeds 6600 volts

FIG. 4.

of giving. The cable to be tested is connected in this case on the high-tension side of the step-up transformer (see Fig. 4).

The induction regulator must not be confused with resistance devices, choke coils, or transformers with tappings brought out on either the primary or the secondary sides. The resistance method invariably involves loss of power, while choke coils or reactances are pressure absorbers, and although more efficient than resistances, have a disastrous effect upon the power factor of the system. Transformers with tappings have the very great disadvantage that the voltage can only be varied in definite steps, and it will be appreciated that this method is very dangerous when cable testing as it may give rise to dangerous oscillations in the cable. Also such transformers have to be provided with a very complicated switching device, which is a very objectionable feature in performing a test in a mine and is entirely eliminated in the induction regulator. Generally speaking, the larger must a transformer be to deliver a given output without overheating. A transformer designed for a given output and frequency can therefore be used on a higher frequency at the same output with somewhat reduced heating. If operated on a lower frequency the transformer will run hotter. When the frequency is reduced the flux density in the iron must be increased in order to work at the same voltage. This sometimes necessitates the use of an excessive magnetization current, so that very great care should be taken when connecting a transformer to a circuit of lower frequency than that for which it was designed.

Naturally the induction regulator having an air-gap takes a larger magnetizing current than an ordinary transformer of similar output.

Induction regulating transformers are somewhat inductive, and this is a desirable feature when used in conjunction with cables possessing capacity, as it prevents dangerous oscillations in the cable.

When an induction regulator is used for cable testing in conjunction with a step-up transformer, the capacity of the induction regulator is only one-half that of the step-up transformer. The primary of the induction regulator would be designed for the supply pressure, while the secondary would be a separate winding designed to furnish a maximum pressure equal to that of the primary of the step-up transformer. This latter pressure would, of course, vary gradually from zero to the maximum, at which value the full output of the transformer would be secured.

The capacity of an induction regulator depends upon the charging currents taken by the cable to be tested at the testing pressure, and this charging current varies with the length of cable, type of dielectric, etc.

A formula is given below for obtaining the capacity current per mile of cable when various data are available. Knowing the testing pressure, the frequency of the system, and the capacity of the cable in microfarads, the capacity current can be calculated from the formula:

$$\text{Capacity current per mile} = \frac{2\pi \times f \times k \times v}{10^6}$$

where f = frequency; k = capacity of cable per mile in microfarads calculated when one core is insulated and the other cores are connected together and earthed; and v = testing pressure between conductors. k can be ascertained from the cable manufacturers for the size and pattern of cable.

Capacity current per mile can be determined for single-core cable from the following formula:

$$k = \frac{0{\cdot}0388 \times \epsilon}{\log_{10}(d_1/d_2)}$$

ϵ = specific inductive capacity, which is about 3·5 for paper-insulated cables, and 6 for rubber-insulated cables.

d_1 = diameter over dielectric.

d_2 = diameter of conductor in inches. If the conductor is made up of a number of strands, the diameter over the strands should be taken.

When testing cables with three cores it is usual to test one core against the other two cores connected together and earthed, and it may therefore be looked upon as a single-phase test. It follows that the above formula gives the capacity current which the induction regulator would have to carry when the test

is carried out under the above-mentioned conditions. Since the period of the test need only be of short duration with long intervals for cooling, the induction regulator can be rated for intermittent service.

Fig. 4 shows the connections between an induction regulator and a three-phase cable. It will be observed that one core of the cable is under test, and the other two cores not under test are connected together and earthed with the armouring of the cable.

Conclusion.

For cable testing in mines the choice of apparatus is governed entirely by the conditions. The main consideration is that a gradually varying pressure is required so that the cable under test will be subjected to a gradual pressure increase from zero to the maximum testing value called for. The author is of the opinion that an induction regulator affords the only solution of the problem.

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EXPLANATION OF ABBREVIATIONS.

(P) indicates a reference to the general title or subject of a paper or address.

(p) indicates a reference to a subject dealt with in a paper or address of which the title is not quoted.

(D) indicates a reference to a discussion upon a paper or address of which the general title or subject is quoted.

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